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CAPSTONE PROJECT REPORT

SHIP UNDERWATER THREAT RESPONSE SYSTEM (SUTRS): A FEASIBILITY STUDY OF ORGANIC MINE POINT-DEFENSE

by

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The Naval Surface Warfare Center Dahlgren Division (NSWCDD) team applied a System's Engineering approach to model and improve upon the Navy's current Mine Counter Measure (MCM) capabilities by addressing the need for ship self-protection measures (SPM). The team initially identified, then made contact with, various MCM stakeholders within the U.S. Navy. This stakeholder interaction allowed for optimized MCM collaboration regarding current operational requirements and capability gaps. Four primary MCM missions were identified and statistically modeled in order to quantify and categorize critical functional characteristics that dictate success in an MCM mission. These modeled data were analyzed to determine the greatest contributing capability area. The team also compared four basic MCM system configurations in order to determine the most appropriate configuration for each primary mission scenario. This report showcases a systems engineering approach to requirements analysis and performance specifics development, which will scope future MCM SPM developmental efforts.

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SHIP UNDERWATER THREAT RESPONSE SYSTEM (SUTRS): A FEASIBILITY STUDY OF ORGANIC MINE POINT-DEFENSE

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The Naval Surface Warfare Center Dahlgren Division (NSWCDD) team applied a System’s Engineering approach to model and improve upon the Navy’s current Mine Counter Measure (MCM) capabilities by addressing the need for ship self-protection measures (SPM). The team initially identified, then made contact with, various MCM stakeholders within the U.S. Navy. This stakeholder interaction allowed for optimized MCM collaboration regarding current operational requirements and capability gaps. Four primary MCM missions were identified and statistically modeled in order to quantify and categorize critical functional characteristics that dictate success in an MCM mission. These modeled data were analyzed to determine the greatest contributing capability area. The team also compared four basic MCM system configurations in order to determine the most appropriate configuration for each primary mission scenario. This report showcases a systems engineering approach to requirements analysis and performance specifics development, which will scope future MCM SPM developmental efforts.

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

AA/DD	Anti-Access/Area Denial
AHP	Analytical Hierarchy Process
ALMDS	Airborne Laser Mine Detection System
AMNS	Airborne Mine Neutralization System
A_O	Operational Availability
AoA	Analysis of Alternatives
AOR	Area of Responsibility
ASW	Anti-Submarine Warfare
BIT	Built in Test
BOE	Back of the Envelope
CAIV	Cost as an Independent Variable
CEP	Circular Error Probability
CONOPS	Concept of Operations
COP	Common Operating Procedure
COTS	Commercial off the Shelf
CPA	Closest Point of Approach
C4I	Command, Control, Communications, Computers, and Intelligence,
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
DoDAF	Department of Defense Architecture Framework
DOE	Design of Experiment
DRM	Design Reference Mission
EFFBD	Enhanced Functional Flow Block Diagram

EMP	Electromagnetic Pulse
EMW	Expeditionary Maneuver Warfare
EOD	Explosive Ordinance Disposal
ESG	Expeditionary Strike Group
E3	Electronic Environmental Effects
GOTS	Government off the Shelf
HOQ	House of Quality
IDEF0	Integration Definition for Function Modeling
INCOSE	International Council on Systems Engineering
JFEO	Joint Forcible Entry Operations
KPP	Key Performance Parameters
LCS	Littoral Combat Ships
LMRS	Long-term Mine Reconnaissance System]
MBSE	Model Based Systems Engineering
MCM	Mine Counter Measures
MEP	Main Effects Plot
MOE	Measures of Effectiveness
MOS	Military Occupational Specialty
MTTR	Mean Time to Repair
M&S	Modeling and Simulation
NOMBO	Non-mine Mine-like Bottom Object
NPS	Naval Postgraduate School
NSWC	Naval Surface Warfare Center
OA	Operational Activity
OASIS	Organic Airborne and Surface Influence Sweep

OMFTS	Operational Maneuver from the Sea
OMOE	Operational Measures of Effectiveness
OPAREA	Operational Area
OPSEC	Operational Security
OPSITS	Operational Situations
OV	Operational View
PCD	Panama City Division
P_d	Probability of Detection
PEO	Program Executive Office
P_k	Probability of Kill
P_i	Probability of Identification
PLAN	People's Liberation Army Navy
PMS	Program Manager Ship
QFD	Quality Function Deployment
RAMICS	Rapid Airborne Mine Clearance Systems
ROC	Receiver Operating Characteristic
ROE	Rules of Engagement
RM&A	Reliability, Maintainability and Availability
RMS	Remote Mine-Hunting System
SA	Situational Awareness
SLOC	Sea-Lines of Communication
SNR	Signal to Noise Ratio
SoS	System of Systems
STOM	Ship to Objective Maneuver
SUTRS	Ship Underwater Threat Response System

TOA	Table of Allowance
TPM	Technical Performance Measures
TTP	Tactics Techniques and Procedures
U.S.	United States
USNR	United States Navy Retired
USV	Unmanned Surface Vehicle
UUV	Unmanned Underwater Vehicles
WWII	World War II
3-D	3 Dimensional

EXECUTIVE SUMMARY

Projecting into the future of mine development and Mine Counter Measures (MCM) indications are that individual surface units will likely be vulnerable to advanced mine technologies. U.S. Naval Forces must be able to operate in the full maritime environment inclusive of the littoral regions in the face of the anti-ship mine threat. An organic point defense capability employed as a part of a layered defense capability with the purpose of detecting and defeating the advanced anti-ship mine will help enhance and ensure operational mission sustainability at both the unit and task force levels (Manke & Christian, 2007).

This report addresses the feasibility of potential point-defense alternatives through the use of the system engineering process to research the following questions:

- How do varying Navy missions impact mine point-defense strategy?
- What is a cost effective anti-mine system?
- What are the critical attributes (and critical attribute thresholds) for system success?
- How can “layered” mine defense improve anti-mine operations’ risk vs. time tradeoff?
- How will future mine technologies drive MCM technology development

It is the recommendation of this report, given the cost of new system development and minimal impact to the risk vs. time tradeoff achieved through technologies modeled in this report, that the Navy continue to investigate the feasibility of new underwater technologies prior to substantially changing the Navy’s development strategy for mine countermeasures. This report recommends the following areas of opportunity for further study:

1. High resolution 3-D sonars (or bathymetry sonars) capable of defining small objects at ranges greater than 100 meters.

2. Advanced digital signal processing algorithms that can provide detection and near optical resolution of fully-buried mine-like objects.

3. Low cost underwater kinetic systems that can engage submerged targets.

4. Advanced non-linear echolocation techniques capable of detecting small objects in turbulence.

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I. INTRODUCTION

A. BACKGROUND

Naval mine warfare has been in existence since the revolutionary war. Though not considered extremely effective 230 years ago, the art and science were well developed by World War II (WWII) and used by all the major warring powers to defend regions through the tactical and strategic policies of anti-access (Benes and Sandel 2009) (Committee for Mine Warfare Assessment, Naval Studies Board, National Research Council n.d.). The first United States (U.S.)-Iraq war demonstrated the effectiveness of mine warfare with the near sinking of the frigate USS Samuel B. Roberts (Cornish 2003). Though crude even by the standards of the day, the mine caused nearly $100 million in damage to the frigate while having a relatively modest cost of approximately $1,500.

A most effective way to limit an adversary's ability to execute military operations is to limit their ability to maneuver within the battlespace and close with your forces. This is the philosophy behind Anti-Access, Area Denial (AA/AD) strategies (McCarthy 2012). The following quote is attributed to Dr. Milan Vego (Vego 2009):

"The success of any major operation or campaign depends on the free movement of one's forces in the theater. Without the ability to conduct large-scale movements on land, at sea, and in the air, operational warfare is essentially an empty concept."

A key component of AA/AD is mine warfare (Manke and Christian 2007). The Chinese People's Liberation Army Navy (PLAN) has had access to former Soviet Technology and has proceeded to develop mine warfare policy as well as advanced mine technology (Truver 2012). These technologies include smart systems that can detect and launch a mine from the sea floor, mines that provide for low detection through advanced materials and shaping, and mines that can also be launched and planted on the sea floor by carrier torpedoes. China is not alone in developing advanced mine technology. France, Spain, Russia and Finland all boast advanced technology mines and sell this technology on the open market placing this ship killing technology in the hands of anyone with sufficient capital and interest.

The U.S. Navy does possess dedicated maritime assets dedicated to the purpose of hunting and sweeping underwater mines in the form of the Avenger Class MCM ship. These ships can be extremely effective in the mine hunting role but because a relatively small number were built, their availability is limited. Additionally, because of the unique design that combines a small size with the use of light composites materials, the Avenger Class ship has limited sea keeping capabilities and generally must be transported for long distance deployments Figure 1. This was demonstrated in the recent deployment of Avenger Class MCM ships to the Gulf under threat of mining from the Iranians (Truver 2012). From an operational stand-point, the Avenger Class MCM ships do not regularly deploy with fleet units unless a need has been identified and the transport logistics can take days to weeks (Benes and Sandel 2009). This means that fleet units may be put on station for days with an existing mine threat with limited means to counter the mine threat.

Figure 1. MCM ships being loaded and transported via dry-dock ship from Truver 2012

New and innovative MCM technologies are needed to provide key transformational capabilities required by the tenets of Sea Power 21 Sea Shield and Sea Strike. MCM technologies are needed to provide the U.S. Navy with the ability to

dominate the battlespace, project power from the sea, and support forces ashore. MCM technologies planned for introduction in the next decade include unmanned systems; remote systems, tethered systems; reconnaissance systems; minesweeping systems; and others (Committee for Mine Warfare Assessment, Naval Studies Board, National Research Council n.d.). Of particular note, systems such as the AN/BLQ-11 and the unmanned remote mine-hunting system (RMS) are intended for a search-only role and the RAMICS system provides a kinetic kill capability only for surface and near surface mines. There is currently no kinetic defense against mines at depths below the keel deployed on individual platforms for the purpose of protecting the platform or nearby assets

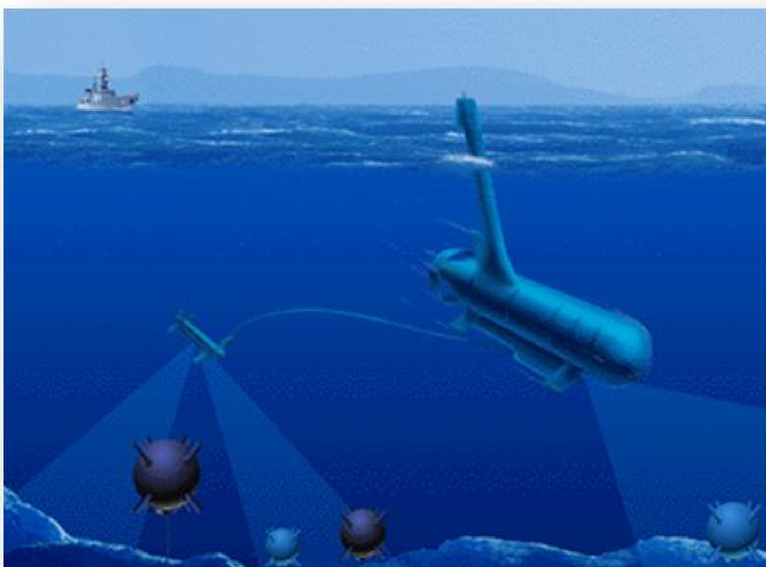

Figure 2. Remote Minehunting System (RMS) from the Committee for Mine Warfare Assessment, Naval Studies Board, National Research Council 2001

The projected future of mine development and MCM indicates that individual surface units will likely be vulnerable to advanced mine technologies. U.S. Naval Forces must be able to operate in the full maritime environment inclusive of the littoral regions in the face of the anti-ship mine threat An organic point defense capability employed as a part of a layered defense capability with the purpose of detecting and defeating the

advanced anti-ship mine will help enhance and ensure operational mission sustainability at both the unit and task force levels (Manke and Christian 2007).

B. SCOPE

The research described in this report investigated a technology gap in the defensive capabilities of U.S. Naval ships to asymmetric underwater threats (e.g., mines). This research will take a particular interest in evaluating the feasibility of a point defense capability.

The asymmetric underwater threat problem space spans the following problem areas: Mission planning, threat detection, threat assessment, and threat response.

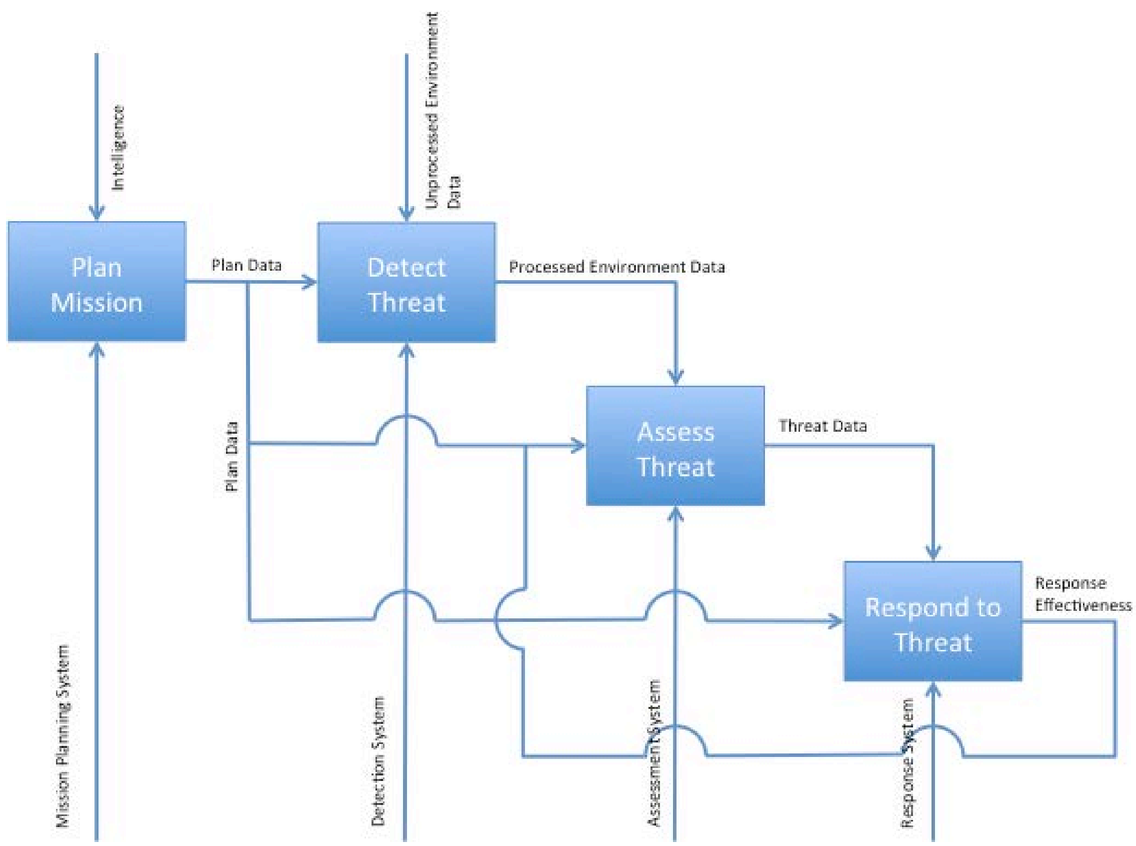

Figure 3. Notional Data Flow

Furthermore, the defense capabilities discussed in this project can be characterized as either passive or active. But at a high level, the four aforementioned

problem areas are applicable in all cases. Those four problem areas are described in more detail in following sections. Figure 3 depicts the notional flow of responding to a mine threat using the four problem areas previously mentioned.

With these problem areas in mind, and the understanding of the mine environment and MCM, this report addresses the following five research questions:

- How do varying Navy missions impact mine point-defense strategy?
- What is a cost effective anti-mine system?
- What are the critical attributes (and critical attribute thresholds) for system success?
- How can “layered” mine defense improve anti-mine operations’ risk vs. time tradeoff?
- How will future mine technologies drive MCM technology development?

This research paper describes the efforts to evaluate the above questions, and the results of the analyses through which the team conducted an assessment of current point defense capabilities. The contents of this report are limited to the Decomposition and Definition components of the systems engineering Vee model depicted in Figure 5. The team performed concept explorations, determined high level concept of operations for operational situations (OPSITS), determined system requirements based on mission needs, stakeholder inputs and environmental factors, developed a high level design architecture, developed models to test the design architecture and further develop operational parameters.

These operational parameters were then used to perform a limited sensitivity analysis. The team performed these tasks in order to answer the five research questions described above. As a final task the SUTRS team performed a preliminary analysis of alternatives using a qualitative Analytic hierarchy Process (AHP) in order to provide a path forward for consideration of promising technologies for a point defense system. The final report does not include a detailed design component nor any of the integration and composition components of the Vee model as this was considered outside of the scope of the project.

C. STATEMENT OF OPERATIONAL NEED

Based on research performed by Dahlgren Team members and conversations with the mine warfare community stakeholders, the following statement of need was developed:

"The U.S. Navy needs a capability to safely perform operations in mined waters."

The SUTRS team is aware of development efforts in the area of remote mine clearance. The probability that an undetected mine remains following clearance operations is substantial. And given the consequences of an undetected mine, detonation, it is the position of the SUTRS team that there is a justifiable need for a layered defense capability for platforms. With that in mind, the SUTRS team identified the following refined statement of need.

> The U.S. Navy needs a capability for Navy platforms to defend themselves from the threat of mines during operations in order to ensure operational mission sustainability at both the unit and task force levels. This capability needs to be adaptable to both legacy and future platforms and must have the system flexibility to integrate current and future technologies.

1. Stakeholder Identification

The team evaluated the many stakeholders and their interests. This evaluation of stakeholders is presented in Table 1.

Table 1. Stakeholder Needs

		Stakes								
		Enhanced Fleet Capability	Reduction in Life-Cycle Cost of Fleet Operations	Reduction in Time of Landing Operations	Enhanced Safety of Operations	Joint Interoperability	Ease of Use	Ease of Maintenance	Follow-On Support	Ability to Prepare for Fleet Operations
Stakeholders	Chief of Naval Operations	x	x		x	x				
	Commandant of United States Marine Corps	x	x		x	x				
	PEO IWS	x	x			x				
	PEO Ships	x	x			x				
	PEO LCS	x	x			x				
	COCOMs	x		x	x		x	x		x
	Support Facility							x	x	
	Trainer						x	x	x	x
	Warfigher			x	x		x	x	x	x

The identification of these stakeholders plays a key role in assessing requirements, functionality, and system architecture of the SUTRS system. Later sections describe the role of these stakeholders throughout the project.

2. System Resource

Having identified the stakeholders and their needs, the SUTRS team analyzed how the stakeholders interfaced with the system and each other. This illustration of need and resource flow is presented in Figure 4. Figure 4 illustrates the flow of system and stakeholder needs that leads to a successful, sustainable system capable of providing safe operations in multiple environments.

In addition to the stakeholders who are documented in Figure 4, the operationally relevant nodes are depicted as well. A high level description of the information/resource exchanges is depicted on the solid and dashed lines.

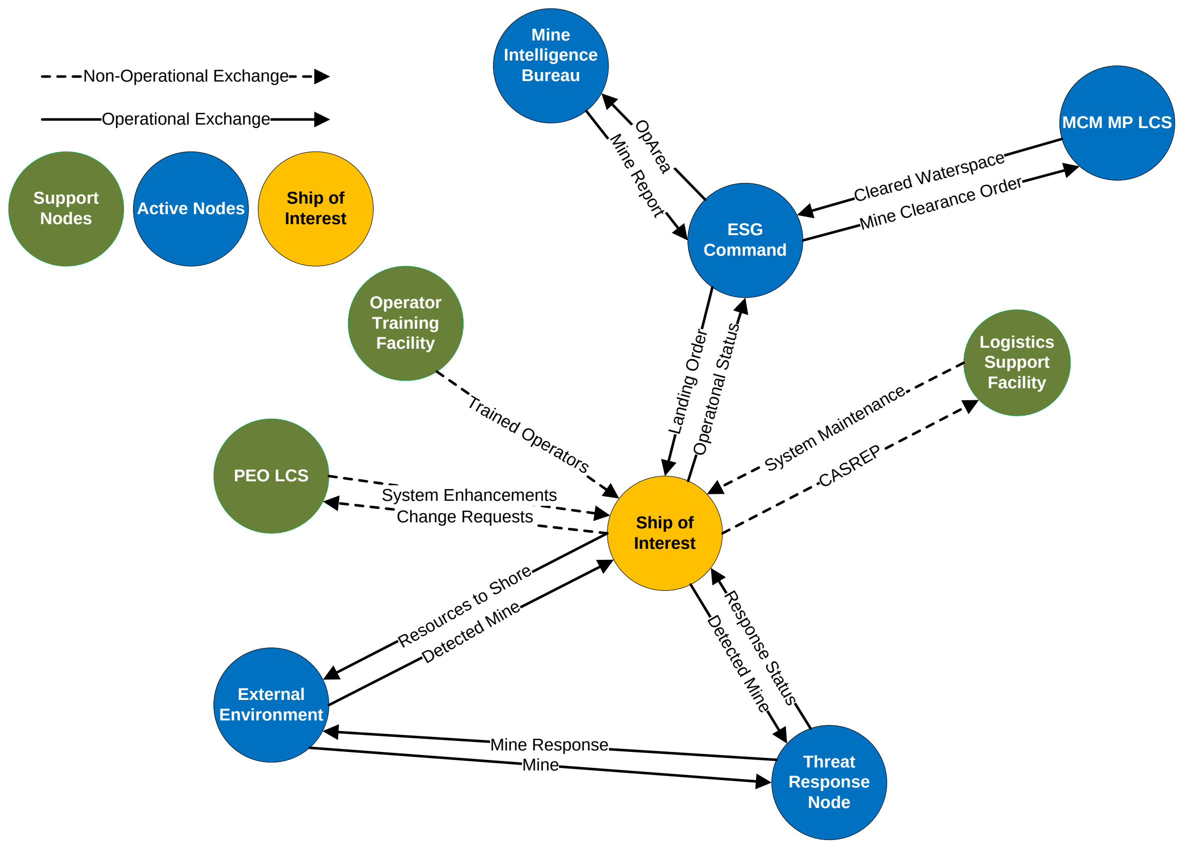

Figure 4. System Resource Flow (OV-2)

D. METHODOLOGY

The following section describes the systems engineering methodology selected for the execution of this project.

The system engineering process for the SUTRS project encompassed the following tasks:

1. Developing an Operational Concept
2. Identifying Stakeholder Needs and Requirements
3. Developing a high level Operational Node Architecture
4. Determining and characterizing the Projected Operational Environment
5. Determining Mission Capabilities based on Stakeholder Requirements
6. Develop a Preliminary Functional Architecture
7. Model, analyze and refine the SUTR System Architecture

This system engineering process follows the “Vee” model in Figure 5. The following sub-sections will describe how the Vee model was used to translate an initial capability need statement into a final product by decomposing capabilities into architecture and requirements, by tracing requirements into design, by implementing and testing the design until a final product has been established that addresses (and has been traced throughout to) the overarching need.

1. Tailored Systems Engineering Plan

Figure 5 below shows the modified Vee model to represent the systems engineering design and development process. It provides guidance for the planning, documentation, and reviews of the project. The Vee Model shows a relationship between the requirements that define the needs from the stakeholders and the verification process to demonstrate that the design and integration solution satisfies those requirements.

A traditional systems engineering “V” shape formation depicts the definition and requirements decomposition on the left side and an integration and verification on the right side. The figure has been modified to show which of the System Engineering steps that this project undertook during this project. It shows the general concept, but does not include detailed product structure levels and iterations on the down stroke and its corresponding layered integration and verification process on the upstroke. This project focuses mainly on the left side of the Vee and will end before a “Detailed Design” is performed.

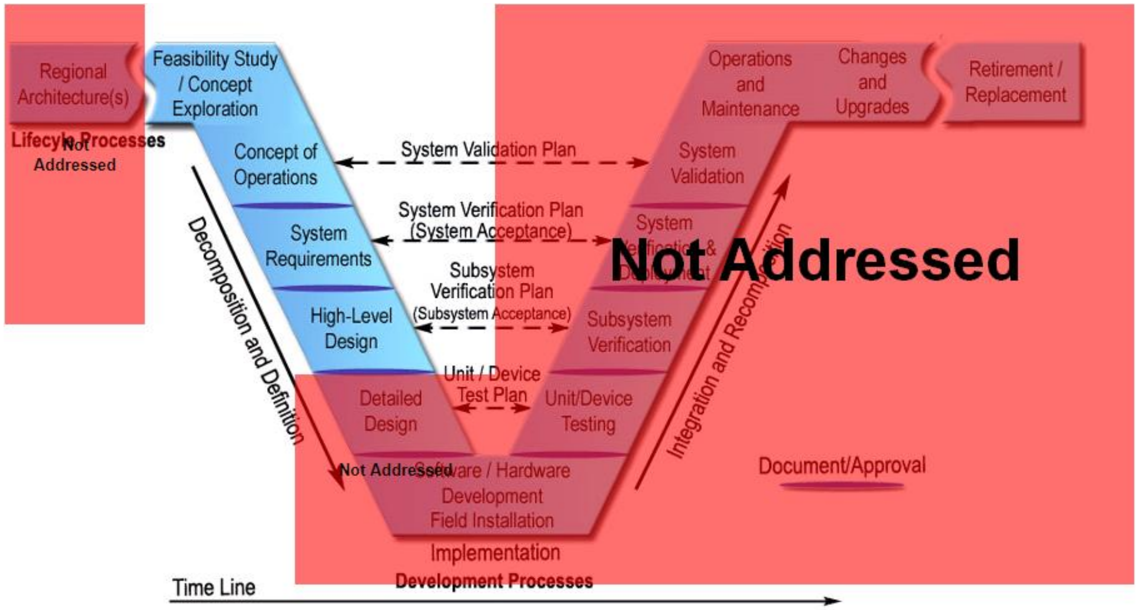

Figure 5. Vee Model of System Development from Blanchard and Fabrycky 2011

2. Feasibility Study/ Concept Exploration

When a deficiency is detected in an area and a system is needed to fill the gap, using the System Engineering process to fill that gap is ideal. At this point in time, there is no organic layered MCM defense on naval ships. In this step, initial research was conducted to determine the details and severity of the technological gaps in MCM and what areas are most in need of assistance. This feasibility study determined if the technology exists to fill this gap or if systems will need to be created.

During this phase the stakeholders were contacted to get their inputs into the project. The stakeholder's ideas about technologies and requirements was documented and noted. A stakeholder analysis was performed to determine which are the most important aspects and requirements of the system. This analysis provided information as to which areas of the system will need specific attention. Following completion of the stakeholder analysis, a needs analysis was conducted in order to determine required system functions, missions, and operational context. The results of this analysis were documented in a Design Reference Mission (DRM).

3. Concept of Operations

An initial Concept of Operations (CONOPS) was developed as a product of the systems engineering effort. A CONOPS is a document that describes the basic characteristics of the system. The CONOPS describes how this system (or system of systems) functions in its intended operational environment once fully developed and integrated. The CONOPS was documented in the DRM.

4. System Requirements

High level system requirements are important to establish verification to specific design and development criteria early on in a project's lifecycle. "The true system requirements need to be well defined and specified and the traceability of these requirements from the system level downward needs to be visible" (Blanchard and Fabrycky 2011). The system requirements were determined from the stakeholder's analysis as well as research into previous MCM systems. Equally important requirements were derived from the mission success criterions of the DRM and were implemented into the Quality Function Deployment (QFD) to ensure the traceability of the requirements from the top down. High level operational requirements which require specific attention are: Mission definition, performance and physical parameters, operational deployment or distribution, operational life cycle, utilization requirements, effectiveness factors, and environmental factors (Blanchard and Fabrycky 2011). High level Key Performance Parameters (KPPs) and Measures of Effectiveness (MOE) were also determined and listed in Sections III.B.2.a. and III.B.3. These system requirements were maintained in CORE and are discussed in Section III.B.2.

5. High Level Design

Although a true high level design was not completed in this project, a high level Analysis of Alternatives (AoA) was performed as well as a Qualitative Cost/Performance Analysis. The project performed research into possible Commercial Off the Shelf (COTs) and Government Off the Shelf (GOTS) equipment that could be utilized for naval

platform point defense. A Qualitative Cost/Performance Analysis was performed to determine if any of the systems found would have a high level of benefit to the Navy without having a high cost.

II. MISSION CONSIDERATIONS

A. INTRODUCTION

The first step in identifying the platform for operational success is to define the operational environment. The team began this research project by developing a DRM. The following section is a collection of relevant excerpts from the DRM. Specifically, this section will describe the assumptions assumption used in follow-on research with regard to threat characteristics, mission threads, inter alia.

B. MISSION

The SUTRS system will need to defend against various threats within different operating environments. The following section describes the overall mission the SUTRS is proposed to accomplish while considering the given threat characteristics and potential operational environments.

1. Operational Concept

The Sub-Surface Threat Response System is a System of Systems (SoS) that enables Navy ships to detect, classify, and neutralize mine-like threats in close proximity to a platforms hull. The Sub-Surface Threat Response System Operational View -1 (OV-1) Product (Figure 6) is derived from the Capability Need Statement, Mission Success Requirements and identified Operational Situations (OPSITs).

As shown in Figure 6, OV-1 depiction provides a high level graphical and textual description overview for the future Navy platform. Included in this depiction is a typical Ship in the U.S. Navy inventory. The needline depiction (lightning bolt) shows required connectivity for the exchange of information between the ship and other generic units concurrently operating in the context environment.

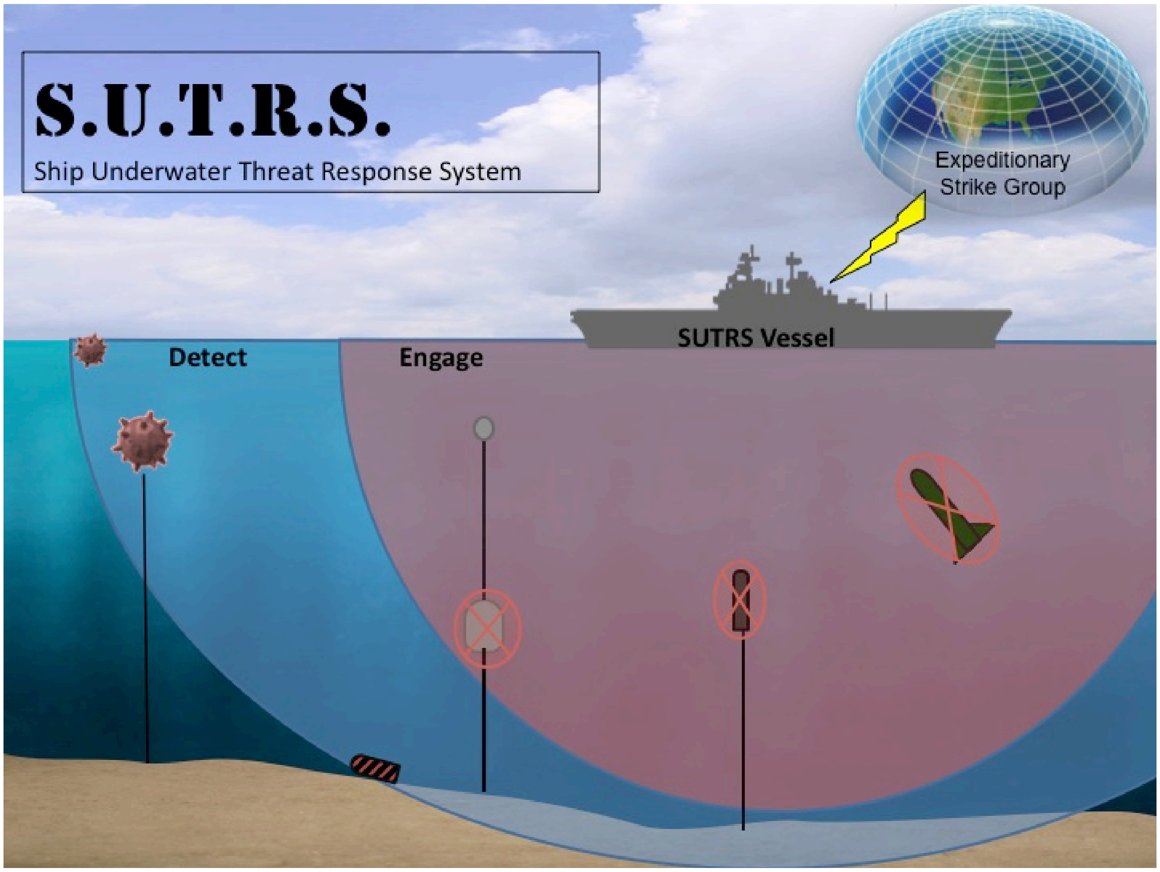

Figure 6. OV-1 Theatre Combat Operation

A vessel enabled with the SUTRS system onboard is tasked by the Expeditionary Strike Group (ESG) to enter potentially mined waters. The platform detects multiple underwater objects, characterizes the threat to the platform, and responds to the threat if required. The SUTRS system will communicate with the ESG to send coordinates of confirmed mines and to send/receive other intelligence.

C. PROJECTED OPERATIONAL SCENARIOS

The SUTRS capability must contribute to the three fundamental operational concepts of Sea Power 21, which encapsulates the U.S. Navy's ability to project offensive power, defensive assurance, and operational independence around the world. These three fundamental concepts are (United States. Office of Chief of Naval Operations, 2003):

- Sea Shield – reassure allies, strengthen deterrence, and protect joint forces through naval capabilities related to homeland defense, sea control, assured access, and defense projection overland.
- Sea Strike – increase operational tempo, reach, and effectiveness through naval power projections leveraging Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance (C4ISR), precision, stealth, and endurance.
- Sea Basing – project U.S. sovereignty globally and minimize vulnerable assets ashore by providing Joint Force Commanders with vital command and control, fire support, and logistics from the sea.

Within these core operational concepts, three OPSITs were established as missions to reference for functional requirements. The anticipated uses of a mine-point defense capability include the following projected operational scenarios (Rhodes and Holder 1998):

- Transiting Sea-Lines of Communication (SLOC)
- Ship to Objective Maneuver (STOM)
- Joint Forcible Entry Operations (JFEO)
- Advanced Clandestine Reconnaissance

These operational scenarios will be used to define anticipated environment characteristics and anticipated threats for the purpose of constructing a detailed OPSIT. In addition, the team identified a fourth potential scenario, Advanced Clandestine Reconnaissance, which was not identified by existing source material, but is relevant to the mine-defense problem space. An overview of each projected scenario is provided in the following sections.

1. Transitioning Sea-Lines of Communication (SLOC)

SLOCs are geographically constrained areas such as choke points, narrows, straits and estuaries around the world. Typically, these sea lines have been and continue to be economically significant lanes of travel and commerce which are considered by all those

who use them to be critical resources to economic prosperity, which makes them easy and obvious targets for mining and other anti-access activities and attacks. The primary Sea Shield functions which must be performed to ensure transit through these SLOCs are accelerated strike positioning, mine marking and avoidance, and high speed of advance mine countermeasures (Rhodes and Holder 1998).

The notional chain of events which would dictate the functions of the SUTRS capability are as follows:

The platform's battlegroup receives intelligence that a critical SLOC has been mined. The battlegroup plans a mission to clear the mines in order to grant access to the waterway. The battlegroup executes the plan and identifies lanes of safe passage. Once safe passage through the minefield has been identified, the battlegroup proceeds through the newly cleared channel. During transit, the platform encounters a mine that was not discovered during mine clearance, and the platform must respond to the mine threat. Follow-On Support and Sustained Operations

2. Ship to Objective Maneuver (STOM)

STOM is a transformational tactical application of enduring naval capabilities for Operational Maneuver from the Sea (OMFTS), which exploits each of the enhanced capabilities described by expeditionary maneuver warfare (EMW). The primary attributes of this Sea Strike activity are tactical surprise, freedom of action and maneuver, and mine countermeasures "in stride." In addition to these attributes, typically there are no prescribed littoral landing lanes and mine countermeasures must be taken prior to main element maneuvers. To achieve tactical surprise for conventional or unconventional (clandestine) forces, MCM activities, which precede primary maneuvers, must maintain a low operational profile, so operational security (OPSEC) dominates the risk equation (Rhodes and Holder 1998).

The notional chain of events which would dictate the functions of the SUTRS capability are as follows:

The platform's battlegroup receives intelligence that the water surrounding a critical strategic objective has been mined. The battlegroup plans a mission to clear the mines in order to grant safe passage to the critical area. The battlegroup executes the plan and identifies lanes of safe passage. Once safe passage through the minefield has been identified, the battlegroup proceeds through the newly cleared minefield and conducts a landing. During the landing, the platform encounters a mine that was not discovered during mine clearance, and the platform must respond to the mine threat.

3. Joint Forcibility Entry Operations (JFEO)

Maritime enabled JFEOs may project power directly against the enemy in a coup de main or may attack across a beach and/or by vertical envelopment to establish lodgment to enable the introduction of follow-on forces. Typically, this Sea Basing activity requires a reduced support footprint during preparation operations which include deliberate and close-in mine countermeasures, maritime environmental surveys, and amphibious landing preparation. The balance of operational tempo versus operational security varies across the range of military operations supported by maritime JFEO. When JFEO is used as a "special operations forces springboard" OPSEC and low operational signature is a key vice assured clearance of all MCM threats (U.S. Armed Forces Joint Staff 2008).

The notional chain of events which would dictate the functions of the SUTRS capability are as follows:

The platform's battlegroup receives orders to station in an operational area (OPAREA) in support of ground forces on land during military operations. The battlegroup plans a mission to clear both the transit corridor and the OPAREA of mines. Following completion of the mine-clearance operation, the platform transits to the OPAREA either during that transit, or during station keeping in the OPAREA, the platform encounters a mine, and the platform must respond to the mine threat.

4. Advance Clandestine Reconnaissance

The platform's battlegroup receives orders to collect intelligence for an OPAREA in preparation for a future mission. The platform plans and executes a clandestine

operation to characterize the OPAREA; identify any threats in the area; and collect general intelligence. Due to the clandestine nature of the reconnaissance mission, the use of dedicated MCM assets may not be feasible due to operational needs of time, tempo, and tactical surprise. During reconnaissance, the platform encounters a mine and must respond to the mine threat.

D. THREATS

Unit Undersea warfare and Mine Counter Measure capability is required by the Sea Power 21 strategy to guarantee freedom of the sea. The SUTRS provides an organic point defense capability to detect, track and engage close subsurface threats, including naval mines, unmanned underwater vehicles (UUV), and combat swimmers.

Due to the cost-effectiveness of asymmetric underwater threats, such as mines, Navy forces will continue to be threatened in all maritime environments and all phases of a mission. Appendix A describes the maritime environments in which the SUTRS is anticipated to be required to operate. The descriptions include environmental characteristics and anticipated threats.

1. Threat Characteristics & Projected Operational Environment

Unit Undersea Warfare and Mine Counter Measure capability is required by the Sea Power 21 strategy to guarantee freedom of the sea. The SUTRS is designed to provide an organic point defense capability to detect, track and prosecute close subsurface mine-like threats within a designated operational area of a platform.

The SUTRS will be comprised of an integrated organic sensor and weapons suite and the maintenance and operation staff required performing the assigned mission under wartime conditions at sea, in harbors and in port. The staff will perform the following:

1. Maintain SUTRS' materiel readiness condition to support fleet unit and task force operations.

2. Provide administrative support to meet operational requirements of deploying personnel.

3. Equip and train system operators.

4. Provide resupply to deployed units.

The most demanding operational environment anticipated for the Sub-Surface Threat Response System is a forward deployed wartime operation within the littoral battlespace, working in conjunction with designated joint forces. These operations are frequently characterized by confined and congested spaces occupied by friends, adversaries and neutral parties.

Due to the cost-effectiveness of sub-surface explosive devices, Navy forces will continue to be threatened in all maritime environments and all phases of a mission (Committee for Mine Warfare Assessment, Naval Studies Board, National Research Council n.d.). Therefore, the Sub-Surface Threat Response System will have to operate in multiple maritime environments and the system will have to be capable of responding to multiple types of current and future threats including a new category of threat known as a maritime Improvised Explosive Device (U. S. Navy 2007). The effectiveness of these threats depends greatly on the depth of water; therefore, the projected operating environments must take into account depth of water (Figure 7).

Table 2 describes the five classifications of operating environment along with the expected threats. Furthermore, Table 2 also delineates an “Other” category for more active threats whose tactics have the capability to evolve in the future (U.S. Navy 2001).

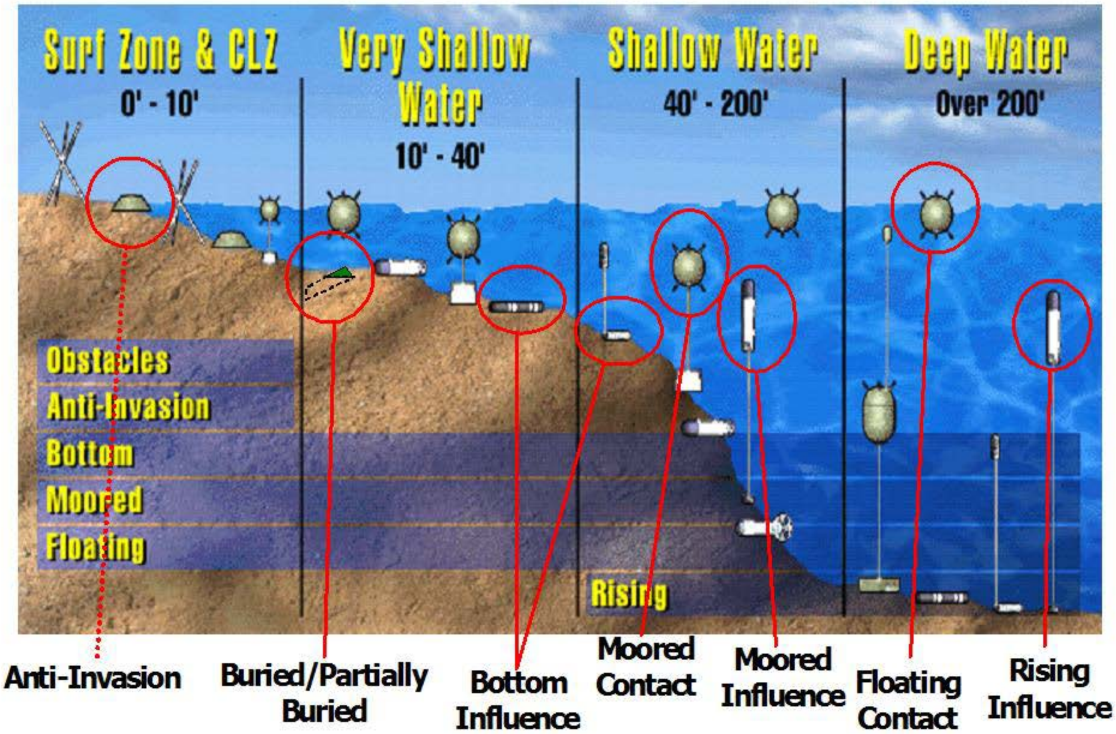

Figure 7. Naval mine depth regimes from PEO0602782N: Mine & Exp Warfare Applied Resolution 2011

Table 2. Threats by Operating Environment

Threat Area	**Depth**	**Potential Threat Type**
Craft Landing Zone	**~0 ft**	**Anti-Personnel Mines and Obstacle**
Surf Zone	**0 - 10 ft**	**Anti-Tank Mines, Anti-Invasion Mines and Obstacles**
Very-Shallow Water	**10 - 40 ft**	**Moored Mines, Bottom Mines**
Shallow Water	**40 – 300 ft**	**Moored Mines, Bottom Mines**
Deep Water	**>300 ft**	**Rising Mines**
Other	**Evolving**	**UUVs**

III. DESIGN SPACE

A. QUALITY FUNCTION DEPLOYMENT

Once the needs from the stakeholders have been determined, consideration for alternative design approaches and concepts would require aiding the system design process through establishing the incorporation of technical characteristics to a design that meets the customer requirements. The QFD's purpose "…is to establish the necessary requirements and to translate those requirements into technical solutions" (Blanchard and Fabrycky 2011). An important part of this project was identifying the stakeholder's wants and transferring those wants into usable applications for the project. A QFD base process was performed in order to prioritize capabilities of the system, trace functionality to identified requirements, and translate top-level requirements into proposed system configurations. In order to perform this analysis, the team performed a three step approach. First, the team performed a pair-wise survey of stakeholders to prioritize the top-level requirements. Second, the team used the compiled results of those surveys in order to assign objective weights to each top-level requirement. Third, the team decomposed the top-level requirements into Technical Performance Measures (TPMs) and system functions (QFD1 and QFD2). The following subparagraphs describe these three analysis steps. The team realizes the following analysis is more so linked House of Quality (HOQ) matrices rather than QFDs, but will continue to refer to the charts as QFDs.

1. Stakeholder Survey

The team created and sent a pair-wise survey to all stakeholders (see Appendix B) for the purpose of identifying the relative value of proposed capabilities as compared to each other capability. The first three questions were used to associate individual responses with identified stakeholder groups. The questions identified that the minimum stakeholder age was 41 years old. A majority of the stakeholders have served in the military as officers and are currently civilian employees or contractors for the federal government. The stakeholders represent a variety of MCM professional experience from Military Users to Intelligence Analysts. These demographic results indicate that the

survey is representative of the mine community. The one potential limitation of the survey is that, due to the age of the stakeholder community, the survey may not reflect the most recent engineering advances.

Ten mission capabilities were identified by the team as being important to the Navy's MCM strategy (Section III.B.2.). Because the purpose of this project was to evaluate the feasibility of organic mine point-defense, the survey asked stakeholders to compare each mission capabilities to Underwater Threat Response. The stakeholders that participated in the survey are as follows:

1. Program Executive Office (PEO) MINEWAR
2. PEO Littoral Combat Ships (LCS), Program Manager Ship (PMS)-495
3. MIW Customer Advocate, Naval Surface Warfare Center – Panama City Division (NSWC-PCD), Code A04
4. Naval Postgraduate School (NPS).

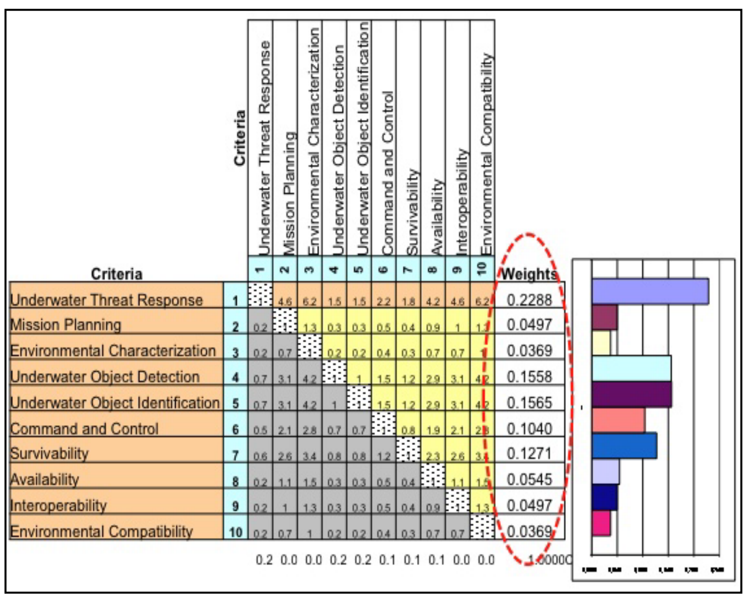

Figure 8. Pair-wise Results

A pair-wise ranking was applied to the responses of the survey. All surveys were weighted equally. Figure 8 shows the results of the rating. The capabilities were calculated and ranked as follows from the pair-wise ranking:

1. Underwater Threat Response
2. Underwater Object Identification
3. Underwater Object Detection
4. Survivability
5. Command and Control
6. Availability
7. Interoperability
8. Mission Planning
9. Environmental Compatibility
10. Environmental Characterization

The pair-wise results give a weighted rank to all of the mission capabilities. These weighted ranks were then plugged into the QFD1 to help determine the relative weighting of the system requirements.

The calculation for the weighted ranks required first to sort the stakeholder survey results into a criteria specification that helped establish a survey value legend as shown in Table 3.

Table 3. Survey Value Legend for Mission Criteria Specification

Survey Value Legend	
Much More Critical	9
Strongly More Critical	7
More Critical	5
Slightly More Critical	3
Equally Critical	1
Slightly Less Critical	1/3
Less Critical	1/5
Strongly Less Critical	1/7
Much Less Critical	1/9

This helped simplify the upkeep organization of each stakeholder input. Each translated stakeholder value for their respective mission capability was summed and then divided by the total number of stakeholders, which were five in our case. The results of those values got implemented to the first row of the pair-wise comparison matrix as shown in Figure 8. The rest of the matrix was logical statements that compared each mission capability to the others. The tallied row summation of multiplying the weight inserted into a respective mission capability multiplied by the total column summation of each mission capability comparison resulted in each weighted rank to all ten mission capabilities.

2. QFD Matrix

A QFD matrix is a tool for translating capabilities to functions to components. The QFD matrix decomposes capabilities, functions, and components while also deriving prioritized weightings based on a non-linear scale. Pair-wise comparisons were used to extract capability rankings since studies have shown that such paired comparisons are a natural decision making process that the human mind utilizes to determine the sense of preference, importance, or likelihood with respect to a certain property that the elements being compared have in common. The fundamental scale of absolute numbers from 1-9 which correspond to verbal comparisons are commonly used to represent comparison judgments derived from stimulus-response surveys and other comparative interactions. Mathematical conditions required for prioritization (ranking) stability dictate that the numerical scale be relegated to a small number of options, homogeneous, and limited to an upper value of 9. By utilizing this fundamental scale, cumulative responses are less likely to result in perturbations or “clumping” caused by sequential associations or greater fidelity (larger numbers of comparative selections) that are restricted in the 1–9 absolute numbers scale (Saaty 2001). By utilizing this proves in three separate sub-matrices, the QFD matrix is able to map capabilities to measures (QFD 1); measures to functions (QFD 2); and functions to components (QFD 3).

Design Characteristic (Hows)

Customer Requirement (Whats)	*Weights*		Time to Plan	Time to Characterize Environment	Probability of Detection	Detection Cycle Rate	Detection Range	Probability of Identification	False Alarm Rate	Mean Time to Identify	Mean Time to Respond	Probability of Success	Magazine Supply	Rate of Fire	Engagement Range	Engagement Depth	Operational Availability	Mean Time Between Failure	Mean Time to Repair	Mean Logisitic Delay Time	
			min	min	unitless (per scan)	Scan / second	m	unitless (per mine)	%	sec	sec	unitless (per mine)	engagements	engagements / sec	m	ft	%	hrs	hrs	hrs	
Underwater Threat Response	0.2288	0.229	1	1	3	3	3	3	3	3	9	9	3	3	9	9	1	1			
Mission Plannning	0.0497	0.050	9	3																	
Environmental Characterization	0.0369	0.037		9												1					
Underwater Object Detection	0.1558	0.156	1		9	9	9										1	1			
Underwater Object Identification	0.1565	0.156	1		3		3	9	9	9							1	1			
Command and Control	0.104	0.104			1		1	1	1	1	9	3		3	3		1	1			
Survivability	0.1271	0.127															3	9	3		
Availability	0.0545	0.054			3	3		3				3	3				9	3	9	9	
Interoperability	0.0497	0.050									3				1		1	1	3	1	
Environmental Compatibility	0.0369	0.037		1	1		1	1	1	1	1	1		1	1	3	3	3	1	1	
Check Sum		1.00																			
Weighted Performance			1.0	0.7	2.9	2.3	2.7	2.4	2.2	2.2	3.2	2.6	0.8	1.0	2.5	2.2	1.7	2.1	1.1	0.6	34.1
Percent Performance			0.029	0.022	0.084	0.066	0.079	0.070	0.065	0.065	0.093	0.075	0.025	0.030	0.072	0.065	0.049	0.062	0.031	0.017	

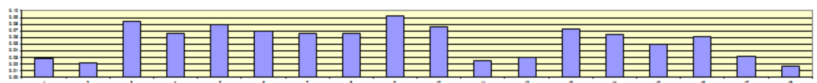

Figure 9. QFD1 Mission Capabilities to Performance Metrics

Figure 9 is an illustration of the QFD process. The left side of the QFD identifies the stakeholder requirements along with the attribute priorities. These priorities are ranked in a quantitative manner based off the pair-wise rankings calculated and shown in Figure 8. The top of the matrix, highlighted in blue, identifies the key technical responses to the needs along with the target technical level that each characteristic should achieve to reach its threshold or objectives. These threshold and objectives were calculated based off of research and assumptions determine by the team.

The results of the QFD1, illustrated in Figure 9, clearly indicate that the three most critical performance metrics were mean-time to respond, probability of detection, and detection range.

The QFD2 mapped performance metrics, discussed in QFD1, to system functions. This helped to further identify the design concept in support of a future AoA.

Design Characteristics (Whats)	Weights		Detect Underwater Objects	Identify Underwater Objects	Neutralize Underwater Objects	Avoid Underwater Objects	Defend (Passive) Against Underwater Objects	Command and Control Underwater Engagement	Travel to Mine	Navigate	Characterize Environment	Plan Mission
			Units	Units	Units	Units	Units	Units	Units	Units	Units	Units
Time to Plan	0.029	0.029						1			3	9
Time to Characterize Environment	0.022	0.022						1			9	1
Probability of Detection	0.084	0.084	9	3					3	1	1	1
Detection Cycle Rate	0.066	0.066	3									
Detection Range	0.079	0.079	9	3						1		
Probability of Identification	0.070	0.070	3	9				1	3	1	1	1
False Alarm Rate	0.065	0.065	3	9				1	1			1
Mean Time to Identify	0.065	0.065		9				3	3			1
Mean Time to Respond	0.093	0.093			3	3		9	3			1
Probability of Success	0.075	0.075			9	9	9	3	3	1	1	1
Magazine Supply	0.025	0.025			1							
Rate of Fire	0.030	0.030			3			1				
Engagement Range	0.072	0.072	3	3	9					1		
Engagement Depth	0.065	0.065			3							
Operational Availability	0.049	0.049	3	3	3	1	1	3	3	3		
Mean Time Between Failure	0.062	0.062	3	3	3	1	1	1	3	3		
Mean Time to Repair	0.031	0.031	1	1	1	1	1	1	1	1		
Mean Logisitic Delay Time	0.017	0.017	1	1	1	1	1	1	1	1		
Check Sum	1.000	1.00										
Weighted Performance			2.7	2.9	2.3	1.1	0.8	1.7	1.6	0.8	0.5	0.7
Percent Performance			0.176	0.191	0.151	0.074	0.055	0.114	0.106	0.050	0.034	0.049

Functions (Hows) — Weighted Performance total: 15.2

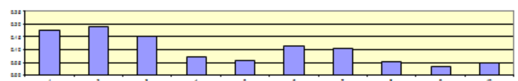

Figure 10. QFD2 Performance Metrics to Functions

The results of the QFD2 (Figure 10) indicate that the three most critical functions are: Identify Underwater Objects, Detect Underwater Objects, and Neutralize Underwater Objects.

Due to the focus on concept exploration, the research paper in intended to support identification of candidate systems for composing a physical architecture. For this reason, a QFD 3 was not performed.

B. BUILDING SUTRS SYSTEMS ARCHITECTURE

Prior to defining an appropriate functional architecture for the SUTRS, the team had to:

1. Define the operational environment within which the SUTRS must successfully deploy and operate.
2. Develop operational concepts
3. Identify the stakeholder needs and define the key performance parameters

4. Develop a high level Operational Node architecture based on the identified needs

1. Operational Nodes

a. Node Context

Figure 11 depicts the high level operational nodes relevant to the SUTRS Architecture. High Level Operational Nodes lists the high level nodes with their primary purpose. The threat areas described in Table 4 are defined by various oceanographic characteristics described in Appendix A. Table 5 lists the level 2 external nodes relevant to the SUTRS functional architecture.

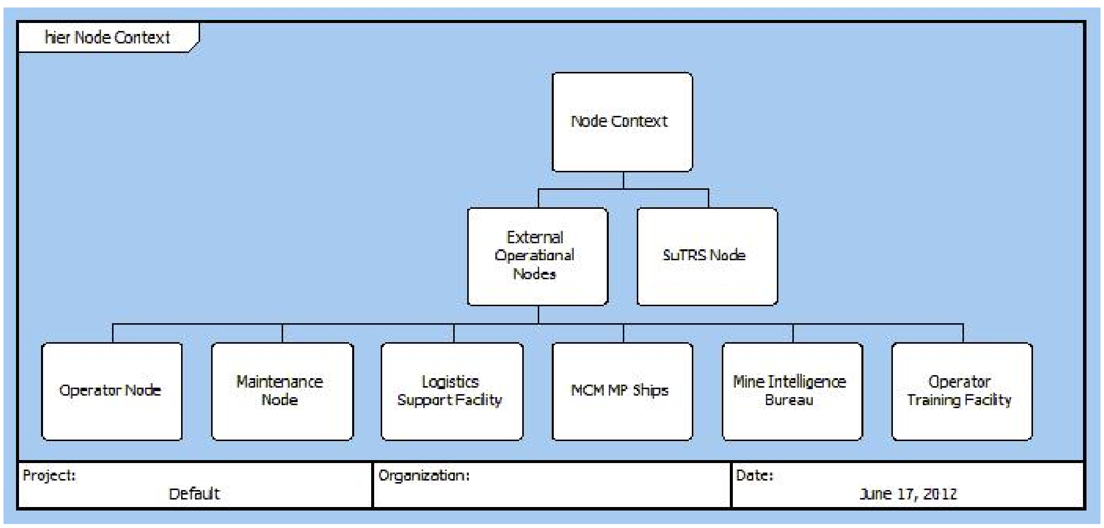

Figure 11. Node Context Hierarchy

Table 4. High Level Operational Nodes

Operational Node	Primary Node Function
Node Context (Level 0)	This element is used to encompass all the top level operational nodes in the model via the "built from" relationship, so that all these components can be viewed in a context diagram.
External Operational Nodes (Level 1)	This element represents the collection of operational nodes that are external to the system under design. This element performs operational activities outside of the system boundary but is expected to interact with the system during its operation.
SUTRS Node (Level 1)	This element represents the top level operational node of the SUTR system under design. It is a highly mobile system and can be deployed to platform that supports Mine Warfare operations. The System searches, detects, localizes, classifies, and identifies mine, mine-like threats. The System is deployed to the unit and taskforce level. The children of this element will constitute the hierarchy of logical elements that produce, consume, and process information within the system boundary.

Table 5. External Operational Nodes

External Operational Node (Level 2)	Primary Node Function
Operator Node	This element represents the human operator that must provide one of several interfaces between the SUTRS node and other external operational nodes.
Maintenance Node	This element represents the collective nodes that provide parts and logistics for the maintenance, repair, and replacement of SUTRS components.
Logistics Support Facility Node	This element performs logistics activities outside of the system boundary and supports the maintenance functions as well as transport and delivery of required system components.
MCM MP Ships	This element performs activities outside of the system boundary necessary to deploy the SUTRS system during its operation. This element is physically represented by the host platform.
Mine Intelligence Bureau	This element performs intelligence activities and can be considered outside of the system boundary but is expected to interact with the system during its operation providing intelligence data such as environmental conditions, suspected locations and types of threats.
Operator Training Facility	This element performs SUTRS training activities and can be considered outside of the system boundary. This element provides the necessary training and education to STRS operators and command personnel to maintain mission readiness.

2. Mission Capabilities

The Objective Sub-Surface Threat Response System capability will employ a wide range of networked Command, Control, Computers, Communications, and Intelligence (C4I) nodes. The mission accomplishment will be achieved through the following criteria:

- Employment: External C4I Interfaces, data, sensors
- Training: Personnel trained to conduct the Sub-Surface Threat Response System
- Leadership: Clear commander's intent and climate that fosters innovation
- Maintenance: Neck-down in maintenance military occupational specialty (MOS), enhanced built in test (BIT), and component replacement
- Equipment: Resident C4I Node, sensors and communications

The success of the Sub-Surface Threat Response System depends on the system's ability to accurately detect sub-surface threats and reliably coordinate an effective response. This high-level statement of mission success criterion has been decomposed into eight mission categories with thirty-five mission sub-categories, and eight KPPs. The KPPs are described in Table 6.

MC.1 Underwater Object Detection/Identification

System will be able to detect and characterize all underwater objects within a specific minimum range of the platform.

MC.1.1 Detection Sensitivity: The SUTRS shall detect sub-surface threats including mines and mine-like objects with a minimum aperture size as described in the requirements.

MC.1. 2 Object Tracking: The SUTRS shall track sub-surface threats including mines and mine-like objects providing range and bearing.

MC.1.3 Object Density: The SUTRS shall be able to track multiple objects.

MC.2 Underwater Object Identification

The SUTRS shall provide for the automatic identification of sub-surface threats including mines and mine-like objects with a displayed level of confidence.

MC.2.1 Identification Resolution: The SUTRS will be able to provide identification metrics of detected objects with confidence levels in real time.

MC.2.2 Identification Update: The SUTRS identification function will provide identification confidence updates at minimum time intervals indicated in the requirements.

MC.3 Command and Control (C4I) Interface

System will provide comprehensive capabilities necessary for command, control, communications, computers & information between the SUTRS and other mission assets.

MC.3.1 Information Distribution and Display: System will share status information, alerts, chat, checklists, reference material and collaborative links between systems as necessary to provide a common operating picture (COP) for commander's situational awareness (SA)

MC.3.2 System Ready Status: System will provide visual and audible cues to the SUTRS operator as to the status and health of the SUTRS. This information will also be made available to the unit commander via capability MC.2

MC.3.3 ROE: The SUTRS shall provide a capability to support Combat Command’s Rules of Engagement (ROEs)

MC.3.4 Data Exchange: The SUTRS shall support communication, networking, and exchanging intelligence data in formats required for proper information interchange between components.

MC.4 Underwater Threat Response

System will eliminate or otherwise make harmless underwater objects determined to be a critical threats to the surface unit.

MC.4.1 Probability of Hit: The SUTRS shall have the capability to engage a target at a minimum range of 100 meters as indicated in the System Requirements. The

SUTRS shall be able to engage a target at range with a circular area of probability not to exceed 2 square meters.

MC.4.2 Depth of Magazine: The SUTRS shall have a magazine capacity to engage a minimum number of targets before exhaustion as indicated in the System Requirements.

MC.4.3 Rate of Fire: The SUTRS shall have a minimum kinetic time to engagement threshold and minimum time to re-engagement threshold as indicated in the System Requirements

MC.4.4 Operational Depth: The SUTRS shall be able to operate and engage targets at depth thresholds as indicated in the System Requirements

MC.4.5 Mean Time to Respond: The SUTRS system shall be operational upon initiation within a time threshold as indicated in the System Requirements

MC.4.6 Engagement Autonomy: Engagement system will provide for varying levels of autonomy to include manual operation and auto-special operation with manual override at the discretion of the unit commander. Engagement will be within 750 ms (Threshold) / 500 ms (Objective) of command signal

MC.4.7 Engagement Status: The SUTRS shall provide a capability to report engagement status such as current load-outs, expended loads, and current functional status.

MC.5 Survivability

The SUTRS will have the capability of operating in an operationally contested environment to include natural and man-made environmental conditions.

MC.5.1 Natural Environment: The SUTRS shall provide a capability to operate in the environments defined in the SUTRS DRM

MC.5.2 Electromagnetic Environment: The SUTRS shall withstand Electromagnetic Pulse (EMP) and other Electronic Environmental Effects (E3) as defined in MIL-STD-461 and MIL-STD-464.

MC.5.3 Environmental Jamming: The SUTRS shall have the capability to overcome jamming of communication and sensor data.

MC.6 Availability

The SUTRS system shall demonstrate system availability as outlined in the DRM. The SUTRS shall meet or exceed an Operational Availability (A_O) of 0.90 (Threshold) / 0.95 (Objective)

MC.6.1 Reliability: The SUTRS system shall demonstrate a system reliability for mission completion of 0.90 (Threshold) / 0.95 (Objective).

MC.6.2 Maintainability: The SUTRS system shall demonstrate system maintainability as outlined in the DRM

MC.6.2.1 MTTR: The SUTRS shall have a Mean Time to Repair (MTTR) of 3 hours (Threshold) / 1 hour (Objective).

MC.6.2.2 BIT: The SUTRS shall provide a capability to perform BITs.

MC.6.3 Supportability

The SUTRS system shall demonstrate system supportability as outlined in the DRM

MC.6.3.1 Logistical Support: The SUTRS shall provide the logistical support to sustain the SUTRS assets already within the Area of Responsibility (AOR) for 20 additional days.

MC.6.3.2 Training and Simulation: System will be capable of providing simulated threat information and response for the purposes of training and sustainment of operational readiness.

MC.7 Interoperability

The system shall have the capability to integrate current and future sensor systems through a common physical and data interfaces based on open system architectures.

MC.7.1 Open Systems Architecture: The SUTRS shall utilize open system architecture that allows for plug and fight capabilities

MC.8 Environmental Compatibility

The system will be capable of operating in the maritime environment under differing conditions of temperature, pressure (depth from surface), salinity, and sedimentation. System will operate with minimal degradation in chemically degraded environments that include heavy fuel oils, light fuels such as kerosene or gasoline, alkaline and acids.

MC.8.1 Environmental Factors: The SUTRS shall meet military requirement (MIL-STD-810G). MIL-STD-810G test series addresses a broad range of environmental conditions that include: low pressure for altitude testing; exposure to high and low temperatures plus temperature shock (both operating and in storage); rain (including wind blow and freezing rain); humidity, fungus, salt fog for rust testing; sand and dust exposure; explosive atmosphere; leakage; acceleration; shock and transport shock (i.e., triangle/sine/square wave shocks); gunfire vibration; and random vibration

MC.8.2 Shock: The SUTRS shall operate without degradation following a Shock Test in accordance with MIL-S-901D.

MC.8.3 Vibration: The SUTRS shall operate without degradation following a Vibration Test in accordance with MIL-STD-167B. The vibration frequency was swept from 4 to 22 Hz. MIL-STD-167B requires an exploratory vibration test (10-minute resonance survey sweep) a variable frequency test (5-minute dwell at each frequency) and a 2-hour endurance test at the resonant frequency. Vibration levels to be used for design and test of equipment shall be derived in accordance with MIL-STD-810, with appropriate modifications based on the SUTRS configuration.

8.3.1 Control and display vibration shall conform to the requirements of MIL-STD-1472, Paragraph 5.8.4.2

MC.8.4 Corrosion: The SUTRS shall operate following the application of measures required to meet corrosion prevention and control as specified in MIL-STD-1568

MC.8.5 Sea State: The SUTRS shall demonstrate operational capabilities as listed in the KPPs in Seas State conditions through Sea State 5.

MC.8.6 Temperature: The SUTRS shall [a] operate in a temperature range of 33to 120 degrees Fahrenheit (F). During non-operating conditions the system shall [b] withstand a temperature range of 0 degrees F to 140 degrees F.

MC.8.7 Personnel Safety: The SUTRS shall include protection of personnel from electrostatic and electromagnetic shock hazards. Where protection by design is not feasible, adequate safety precautions shall be included in operating and maintenance manuals. Requirement 1 of MIL-STD-454 shall be used as a guide.

a. Key Performance Parameters

During the prior QFD analysis, the team documented a small set of assumptions and used those assumptions to generate Threshold and Objective values for multiple TPMs. The assumptions used to evaluate those TPMs are as follows:

- The threshold Probability of Success for the total system should be 90% survival.
- The objective Probability of Success for the total system should be 95% survival.
- The blast radius for a mine is 60m (Holmes 2006)
- Ship's speed in a minefield is 5 knots. (10 m / second)
- In poor bottom conditions, the detection range will be poor (assumed a range of 200m).

With this set of starting assumptions, it was determined that the platform would have a 14 second window of opportunity to defend itself from the mine. The remaining TPMs were derived from these assumptions.

Additionally, the analysis looked at Reliability, Maintainability, and Availability (RM&A) values. Again, the analysis began with a few basic assumptions:

- Due to criticality of the function, there is one system and one spare.
- The system (with spare) should achieve a mission reliability of 90%.

Using these assumptions and the RM&A equations in the analysis also identified threshold and objective values for Operational Availability, Mean Time Between Failures, and Mean Time to Repair (Blanchard and Fabrycky 2011).

Some of those TPMs, based on the results of the QFD analysis were identified as KPPs. These KPPs are described in Table 6.

Table 6. Key Performance Parameters (KPPs)

Key Performance Parameters	**Threshold**	**Goal**
KPP.1. Detection Range	200 meters	1000 meters
KPP.2. Average False alarm rate	0.98	0.995
KPP.3. Engagement Range	100 meters	500 meters
KPP.4. Operational Availability	0.80	0.95
KPP.5. Mean Time Between Failures	4000 hours	5000 hours
KPP.6. Maintainability	MTTR = 3 hours	MTTR = 1 hour
KPP.7. Survivability	Environmental Test Standards as cited in the DRM (U.S. Navy OPNAV Instruction 9070.10 n.d.) (U.S. Navy OPNAV 3401.3A n.d.)	
KPP.8. Simultaneous Object Detection and Tracking	5 objects	8 objects

3. Mission Definition and Execution

The following preliminary high level operational activities are identified below for this DRM. The top level operational activity is the foundation of the program where as the first level operational activities are the children to OA.0. The traceability of these functions for the future subsurface defense capability is displayed in Table 7.

<u>Top Level SUTRS Operational Activity:</u> OA.0 Perform SUTRS Activities (Defend surface units)

<u>First Level Operational Activities:</u>

- OA.1 Detect/Track Threat
- OA.2 Perform SUTRS C4I

- OA.3 Identify Threat
- OA.4 Engage Threat
- OA.5 Simulate Threat
- OA.6 Determine System Health Status
- OA.7 Display Common Operational Picture (COP)

Table 7. Operational Activity to Mission Capability Mapping

High Level Mission Capability (BCEC)	Related High Level Operational Activity
MC.1 Underwater Object Detection/Tracking	OA.1 Search/Detect/Track Threat
MC.2 Object Identification	OA.3 Identify Threat
MC.3 C4I Interface	OA.2Perform SUTRS C4I OA.7 Display COP
MC.4 Underwater Threat Response	OA.4 Engage threat
MC.5 Survivability	OA.0 Perform SUTRS Activities
MC.6 Availability	OA.0 Perform SUTRS Activities EXT.OA.2 Maintenance Activities OA.6 Determine System Health Status OA.5 Simulate Threat EXT.OA.2 Maintenance Activities OA.0 Perform SUTRS Activities
MC.7 Interoperability	OA.0 Perform SUTRS Activities OA.2 Perform SUTRS C4I OA.7 Display COP EXT.OA.1 Conduct External Operational Activities
MC.8 Environmental Compatibility	OA.0 Perform SUTRS Activities

The mission capabilities for the future subsurface marine defense are mapped to corresponding zero and first level operational activities. Certain mission capabilities are mapped to the zero level since they support all operational activities equally.

C. PRELIMINARY SYSTEM ARCHITECTURE

The following sections describe the SUTRS team’s development approach, development, and analysis of the SUTRS System architecture.

1. Model Based Systems Engineering Approach

Due to the nature of the SUTRS problem space (i.e., submerged, hard to detect, explosive devices), pursuing a test driven engineering process proves to be cost prohibitive. Therefore, the SUTRS team pursued a Model Based Systems Engineering (MBSE) approach, wherein the team first identified the necessary system capabilities and translated those capabilities into high-level functional architectures. Having identified the functions, operational nodes, and data items necessary, the SUTRS team defined high-level operational scenarios that could be used to model the architecture. The architecture modeling activities are described in Section III.D.1. This section describes the process of defining the high-level functional architecture.

The CORE® tool implements a MBSE approach to developing an architecture model and any related Department of Defense Architecture Framework (DoDAF) views (Estefan, 2008; Vitech™ CORE®, 2007).

2. Top Level Architecture

The SUTRS team developed a functional model of the core capabilities of the envisioned SUTRS, and created an architecture using CORE®. The created CORE® architectural model includes Integration Definition for Function Modeling (IDEF0) diagrams and Enhanced Functional Flow Block Diagrams (EFFBDs) that can be used to simulate the architecture.

The SUTRS Mission Thread consists of the core capabilities required to perform the SUTRS missions and are listed below:

- Detect/Track Threat,
- Perform C4I,
- Identify Threat,
- Engage Threat,

- Determine System Health Status.
- Simulate Threat
- Display COP.

The SUTRS team chose these top-level activities because, in the presence of a sub-surface threat, in order for safe force-level operations to continue in the threatened water space, the platform or battle group must identify the presence of a threat and respond to the threat.

Threat identification consists of three core capabilities: Detection, Tracking, and Identification. Detection and Tracking were combined because Tracking is an extension of Detection. The primary difference is history. Identification converts raw information into some assessment of level of danger. Given the presence of a threat, the SUTRS will eliminate the sub-surface threat by engaging it by means of Tactics Techniques and Procedures (TTPs), electronic counter-measures, or kinetic means.

Additionally, because a SUTRS mission failure is a catastrophic failure, and because the operational environment is not easily accessible, status monitoring, training, and communication is essential. Therefore, the SUTRS team identified the additional supporting top-level functions of C4I, COP display, threat simulation, and System Status monitoring. The SUTRS functional hierarchy and IDEF0 are depicted in Figure 12 and Figure 13 respectively.

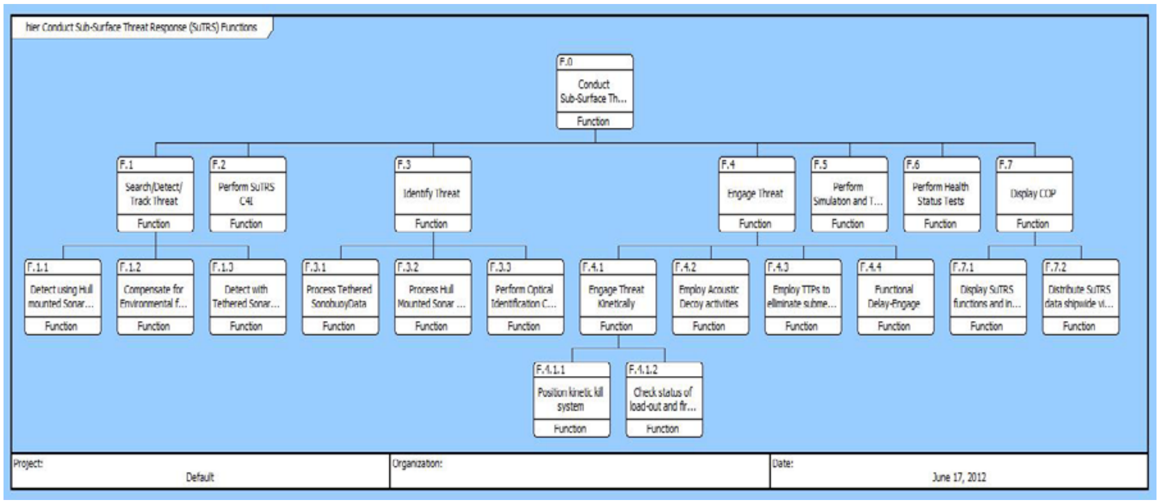

Figure 12. SUTRS Functional Hierarchy

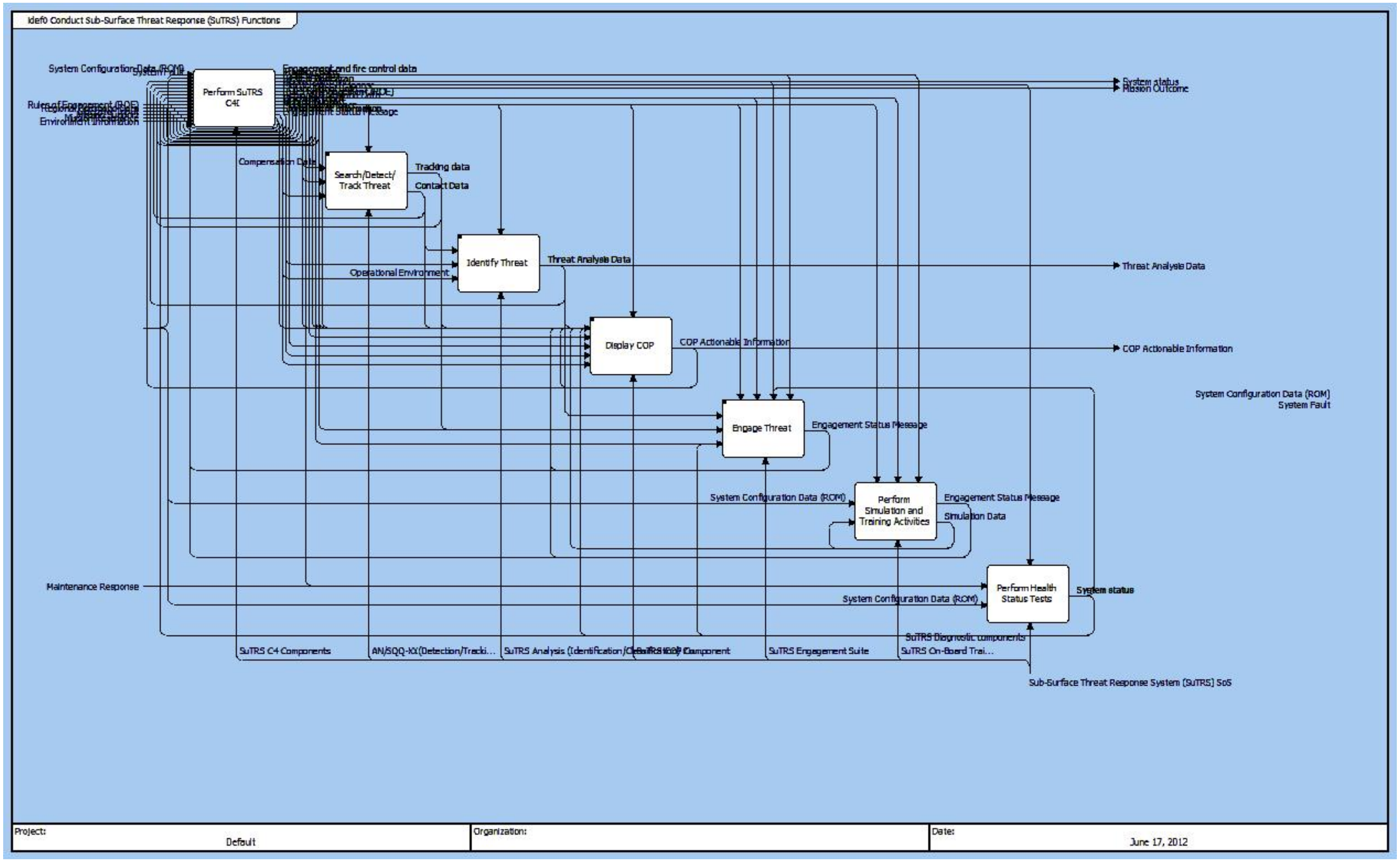

Figure 13. SUTRS Functional IDEF0

3. Interfaces

The interfaces for the SUTRS system are composed of three primary types; functional, physical and environmental. Examples for each type are described in (Grady 2010). Functional interfaces are those which provide a signal between components such as an electrical signal or digitally based signal via a transducer. Physical interfaces are those which must provide a form or fit of mating parts. An environmental interface occurs when the natural environment introduces or communicates environmental stress between elements. Environmental stress could be related to chemical or thermal qualities or ambient qualities such as light and noise. Environmental interfaces are particularly important with respect to Human Factors and Human System Integration.

In this section we focus primarily on the functional interfaces leaving further discussion of physical and environmental interfaces until the discussion of analysis of alternatives (AoA).

Figure 14 depicts the N^2 diagram for the SUTRS System Functional Context. Entities such as external sensor systems, platforms or organizations perform the external functions represented by EXT.F.1 Node and pass the necessary data to the SUTRS for further processing. The SUTRS in turn provides data back to the external systems. This data is passed between the SUTRS and the external entities via “External Data Items” defined within the CORE® architecture model.

Likewise, functional components within the SUTRS also pass data between components via “Internal Data Items” defined within the CORE® architecture. Figure 15 depicts the N^2 diagram for the SUTRS Functional Architecture. The resulting information can also be processed and passed back to external functional entities.

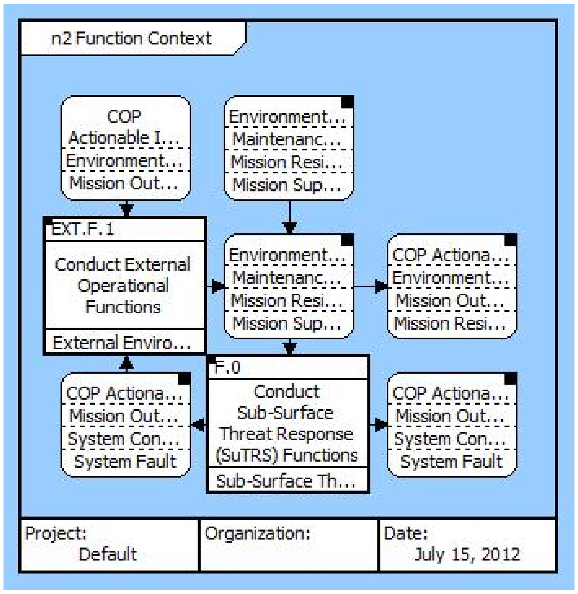

Figure 14. SUTRS Functional Context N^2

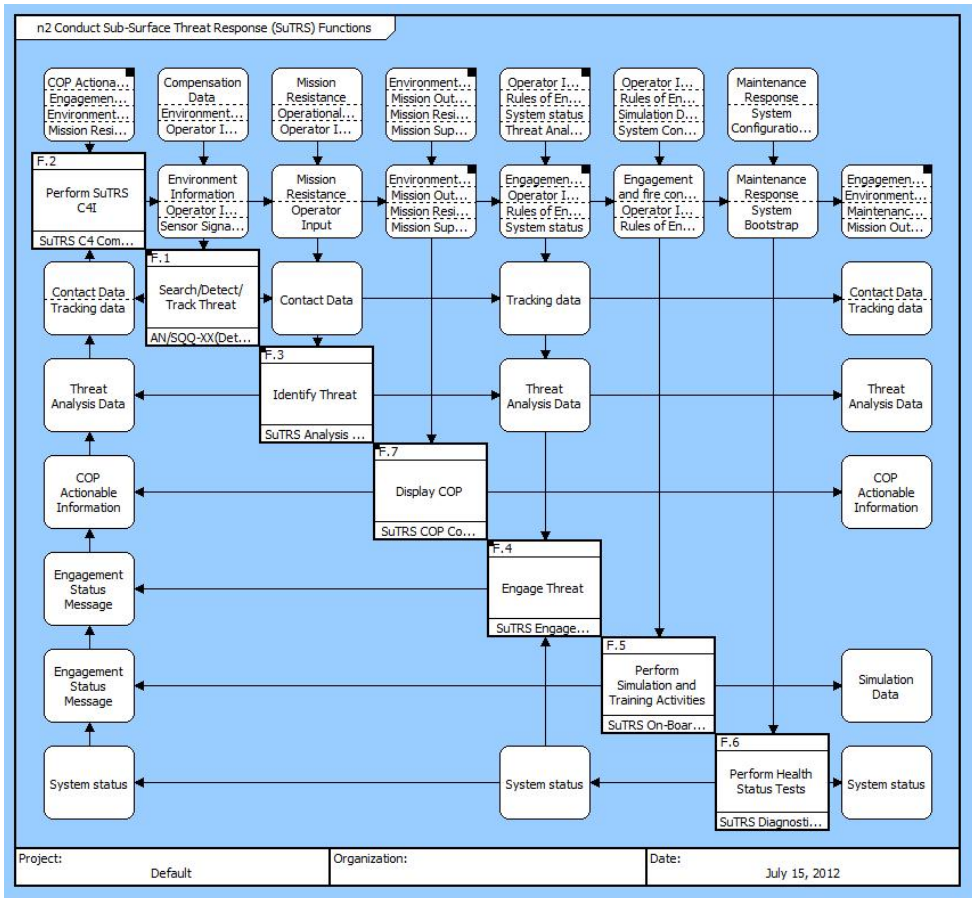

Figure 15. SUTRS Functional Architecture N^2

Table 8 lists and describes the modeled N^2 architecture data items.

Table 8. N^2 Architecture Data Items

EXT.ITM.1	Environment Information	This element represents the sum of information gathered by the system directly from the environment. It is meant to include things like weather, intelligence, position information, etc.
EXT.ITM.1.1	Ambient Water Environmental Information	This is the aggregate information necessary to calibrate sensor equipment for purposes of detection, tracking, identification and engagement.
EXT.ITM.1.1.1	Water Clarity Information	This is information relative to the visibility conditions of the undersea environment with respect to optical, EM and acoustic sensors.
EXT.ITM.1.1.2	Water Contamination Information	This is information relative to the chemical contamination conditions of the undersea environment which can impact optical, EM and acoustic sensors.
EXT.ITM.1.1.3	Water Salinity Information	This is information relative to the salinity conditions of the undersea environment which can impact EM sensors and physical buoyancy considerations for object engagement.
EXT.ITM.1.1.4	Water Temperature	This is information relative to the temperature conditions of the undersea environment that can impact the optical, EM and acoustic sensors.
EXT.ITM.1.2	Operational Environment	This is information relative to population conditions of the undersea environment with respect to both type and numbers of objects.
EXT.ITM.1.2.1	Sub-Surface Object Population Density	This is information relative to holistic population conditions of the undersea environment with respect to numbers of objects.
EXT.ITM.2	Mission Support	This element represents the sum of information deliberately shared by friends and allies in support of the system's mission. This element would be decomposed into the various specific types of information fitting this description.
EXT.ITM.2.1	Friendly Systems Information	This is aggregate information relative to friendly population conditions of the undersea environment with respect to types, purpose and numbers of objects.
EXT.ITM.2.1.1	Numbers, Types	This is information relative to friendly population conditions of the undersea environment with respect to types and numbers of objects.
EXT.ITM.2.1.2	Operational Parameters	Location information, communication protocols, purpose
EXT.ITM.2.2	Threat Objects Encountered	This is information is a characterized metric with respect to unfriendly system population conditions of the undersea environment with respect to types and numbers of objects.
EXT.ITM.2.2.1	Type, Location, Detection Range, Engagement Range, Time to Engage	This is information is a characterized metric with respect to unfriendly system population conditions of the undersea environment with respect to Type, Location, Detection Range, Engagement Range, Time to Engage threat objects
EXT.ITM.3	Mission Resistance Data	This element represents the sum of information deliberately shared or injected with unfriendly or malicious intent with the objective of hindering or resisting the system's mission. This element would be decomposed into the various specific types of information fitting this description.
EXT.ITM.3.1	Acoustic Disturbance Data	This is information relative to the type and intensity of acoustic disturbances encounter within the SuTRS environment.
EXT.ITM.4	Mission Outcome Data	This element represents the sum of information returned to the system's environment as a consequence of the system performing its mission (successfully or unsuccessfully). This element would be decomposed into the various specific types of information fitting this description.
EXT.ITM.5	Regional Command Data	This element represents the sum of information from the COCM in

		support of the mission.
EXT.ITM.6	Operator input	This activity represents the operator's input to the system.
EXT.ITM.7	Maintenance Response	Response item from Depot Maintenance Facility in response to system status (this is a binary response based on status-fix or no fix)
EXT.ITM.8	Platform Availability Data	Schedule availability of the host platform for maintenance
EXT.ITM.9	Rules of Engagement(ROE)	Laws of Armed Conflict and situational policy
ITM.0	SUTRS Data	This element comprises all of the SuTRS collected data sets from detection to engagement to status
ITM.1	Sensor Signal Data	The energy that must be applied to actively detect an object.
ITM.1.1	Compensation Data	Environment Sensor Data for operational compensation factors.
ITM.2	Contact Data	This item represents the sensor data processed with the environment data.
ITM.3	Threat Analysis data	This item represents the processed contact data that has been identified as having hostile intent.
ITM.4	Tracking Data	Data that has been processed to provide tracking information for the engagement system.
ITM.5	Engagement and Fire Control Data	This data is an aggregate of tracking, characterization, and engagement priority data as well as data indicating autonomy status.
ITM.6	Simulation Data	This is data generated through the use of predetermined sets collected for the purposes of training crew and exercising C4I components of the SuTRS.
ITM.7	System Status	This is health status system data generated during SuTRS operations that indicates health and availability status of the SuTRS.
ITM.7.1	Ready Status	Load status for number and type of projectile.
ITM.7.2	Lock Target Status	Status of the articulation Node for physically aligning the targeting system with the threat based on tracking data.
ITM.8	System Fault	This is "just in time" indicator data to indicate a failure in the SuTRS system.
ITM.9	Engagement Status Message	Terminal message from engagement system indicating status of engagement (active, terminated, ready)
ITM.10	System Bootstrap	Element represents data cycling and System Boot checks to determine operational status upon system start-up.
ITM.11	System Configuration Data (ROM)	Baseline System Configuration Data ROM used to determine system status on boot-up
ITM.12	COP Actionable Information	This element represents data and information that is actionable either by the operator, such as warnings and status, but also queries from and to the SuTRS operator to external systems.

4. Operational Scenarios

The SUTRS team identified four high-level scenarios (described previously in Section II.C) requiring the need for mine point defense. The high level scenarios were grouped under two generalized SUTRS OPSITS:

- Coordinated search and engagement OPSIT
  - Ship to Objective Maneuver

- Transiting SLOC
- Joint Forcible Entry Operations
- Advance Clandestine Reconnaissance

  - Simulation Training Engagement OPSIT.

a. Coordinated Search and Engage OPSIT

Figures 16 illustrates the search and engage OPSIT. The purpose of this OPSIT is to provide a high-level description of the SUTRS capability to interrogate and engage contacts communicated to the SUTRS platform from units external to ship.

The coordinated aspect of this scenario focuses on non-peacetime operations. As such, this operational scenario is most relevant to OPSITs as identified in the SUTRS DRM.

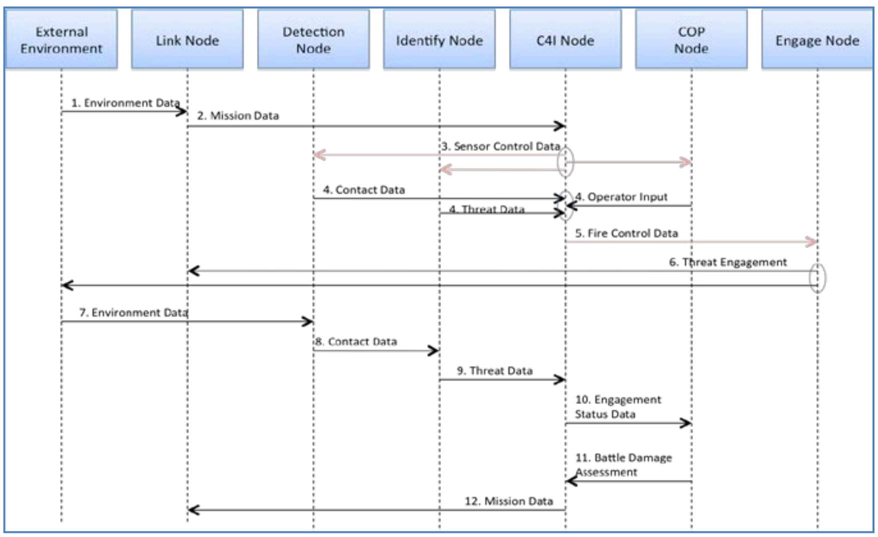

Figure 16. Coordinated Search and Engage Scenario

Description

- A Threat is present in the operational environment.

- A platform external to the SUTRS resident platform sends a mission to eliminate the threat to the SUTRS C4I Node.

- The SUTRS C4I node sends sensor control data to direct the Detection Node to search the OP-AREA, alert the COP to the operator, and contact to the Identification Node.

- The SUTRS Detection Node sends contact data to the SUTRS C4I Node. The Operator receives the mission and inputs commands into the SUTRS C4I Node. The SUTRS Identification Node evaluates the contact data and sends the threat data to the C4I Node.

- Through command and decision, the C4I Node sends Fire Control Data to the Engage Node.

- The SUTRS Engage Node sends threat engagement back via the Link Node for feedback purposes, and engages the threat.

- The SUTRS engagement is either successful or non-successful, which impacts the threat characteristics.

- The SUTRS Detect Node collects updates to existing contacts and sends to the Identification Node.

- The SUTRS Identification Node assesses the new threat level based on the contact updates and sends the revised Threat Data to the C4I Node.

- The C4I Node processes the updated Threat Data and displays Engagement Status Data to the operator.

- The operator processes the Engagement Status Data, determines the success of the mission, and inputs a Battle Damage Assessment.

- The SUTRS C4I Node processes the Battle Damage Assessment and sends Mission Data back to command via the Link Node.

b. Simulation Training Scenario

Figure 17 illustrates the Simulation Scenario. The purpose of this operational scenario is to provide a high-level description of the Sub-Surface Threat Response System's capability to improve system reliability by providing a simulated threat during peacetime training operations.

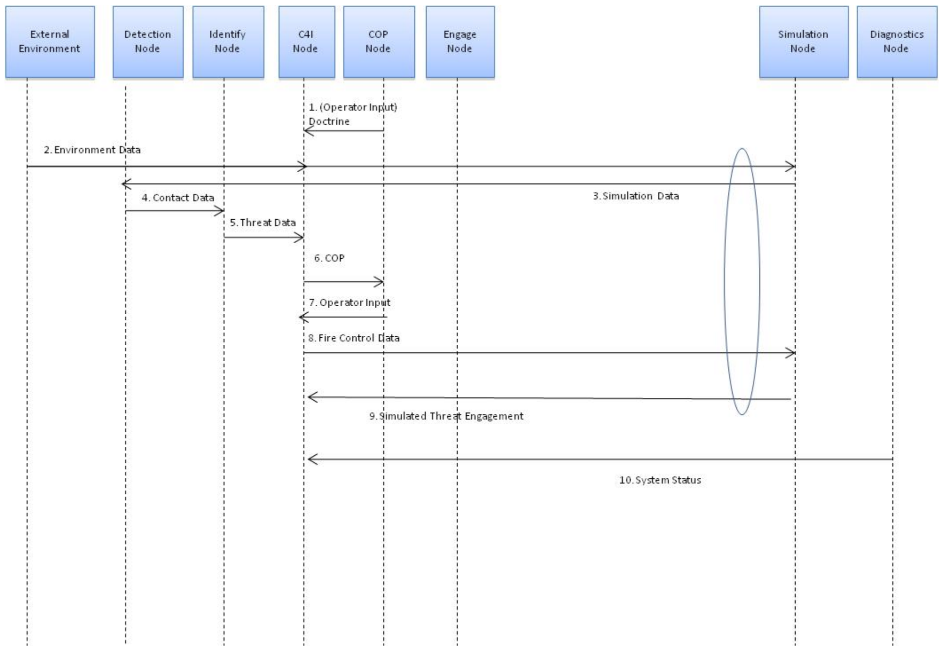

Figure 17. Simulation Scenario (placeholder)

Description:

- Prior to own ship operations, the SUTRS operator loads mission threat templates and rules of engagement—into the C4I Node.
- During training operations, a simulated threat is present in the operational environment and actual environmental data can be introduced into the simulation.
- The SUTRS simulation Node processes the environmental data and sends simulation data to the Detection Node.
- The SUTRS Detection Node processes the actual or simulated Environment Data and sends Contact Data to the Identify Node.

- The SUTRS C4I Node sends simulation data to the COP Node for engagement analysis and operator inputs respectively.

- Through command and decision, the C4I Node sends Fire Control Data to the Simulation Node for simulated engagement.

- The SUTRS Simulation Node engages the threat.

- The SUTRS engagement is either successful or non-successful, which impacts the threat characteristics.

- The Simulation Node processes the simulation data, and sends system status to the Diagnostics Node.

5. Enhanced Functional Flow Block Diagram Models

Using the Operational Scenarios as a roadmap for interface specifications, functional precedence, and data flow, the SUTRS architecture team constructed EFFBDs that could be used to model the overall architecture. These EFFBDs are discussed in the following section.

Figure 18 shows the high-level system context EFFBD for the SUTRS with appropriate control constraints applied to produce the high-level operational activities. Viewing the flow of functions from left to right, it is apparent that the physical architecture must conduct operational activities asynchronously between external functional entities and the SUTRS.

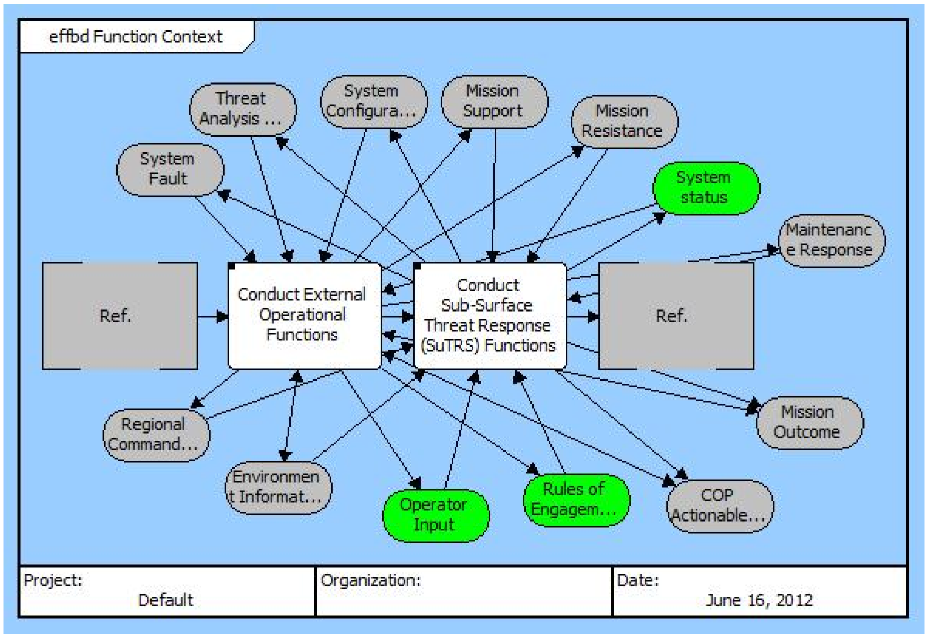

Figure 18. SUTRS Functional Context EFFBD Diagram

The functional activity model for the function "perform SUTRS activities" is shown in Figure 18. The activities from the function "perform SUTRS activities" are

- Perform SUTRS C4I,
- Detect/Track Threat,
- Identify Threat,
- Display COP,
- Engage Threat,
- Simulate Threat,
- Determine System Health Status.

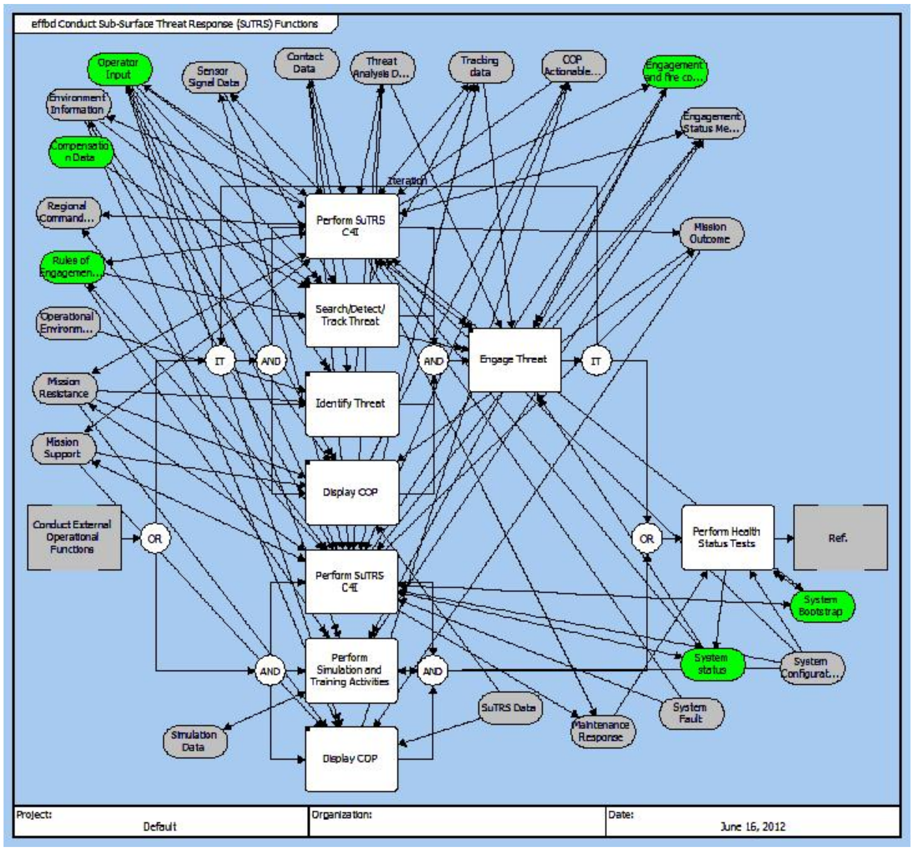

Figure 19. Perform SUTRS Activities Enhanced Functional Flow Block Diagram (EFFBD) with Iteration Loop

The SUTRS activity flow using the EFFBD in CORE® (as shown in Figure 19) represents the functional activity needed to complete a system task type. The SUTRS functional Activities are

- Detect/Track Threat [F.1] - Represents the activity of searching, detecting, and tracking a contact providing this information for further analysis by the system.

- Perform SUTRS C4I [F.2] - Represents the system capability to display and distribute operational environment data, contact data, threat data, and system status information to the operator and any external systems through the external C4I node

- Identify Threat [F.3] - Represents the system's capability to categorize a detected contact's threat level.

- Engage Threat [F.4] - Represents the system capability to respond to a sub-surface threat and neutralize the threat.

- Engage Threat Kinetically [F.4.1] - Operator performs engagement functions through a submerged kinetic kill close in weapon system for torpedo and mine defense.

- Employ Acoustic Decoy Activities [F.4.2] - System deploys acoustic decoy system for counter-detection and spoofing of mines and torpedoes.

- Perform Simulation and Training [F.5] - Represents one of the child activities Simulate of the top level function Conduct SUTRS Functions. This element could constitute a lower level hierarchy of activities performed by the various components making up the Search Function.

- Display COP [F.7] - Provides fused data information, SA and collaboration tools to the SUTRS operators.

- Perform Health Status Tests [F.6] - System provides Health Status via BITs

In Case II, the alternate branch contains

- Perform SUTRS C4I [F.2],

- Simulate Threat [F.5]

- Display COP [F.7] performed in parallel, signified by the AND logic.

- Perform Health Status Tests [F.6] - System provides Health Status via BITs

In both Scenarios I and II, when the remaining function "Determine System Health Status" [F.6] is complete, the flow continues to the end of the process and outputs are produced.

The SUTRS uses items as input and output data stores and/or triggers in support of the SUTRS mission. The functions of SUTRS perform in execution whether a data store is or is not present. But the triggers are modeled as inputs at the higher levels of the architecture and converted to control inputs only at the lowest implementation level in order to allow the simulation to execute.

Data Store Items

- Environment Data [EXT.ITM.1] - Represents the sum of information gathered by the system directly from the environment. It is meant to include things like weather, intelligence, position information, etc.

- Mission Support Data [EXT.ITM.2] - Represents the sum of information deliberately shared by allies in support of the system's mission.

- Mission Resistance Data [EXT.ITM.3] - Represents the sum of information deliberately shared or injected with unfriendly or malicious intent with the objective of hindering or resisting the system's mission.

- Mission Outcome Data [EXT.ITM.4] - Represents the sum of information returned to the system's environment as a consequence of the system performing its mission (successfully or unsuccessfully).

- Regional Command Data [EXT.ITM.5] - Represents the sum of information from the COCOM in support of the mission.

- SUTRS Data [ITM.0] - Represents SUTRS data.

- Sensor Signal Data [ITM.1] -The characterized energy signal that must be transmitted to actively detect an object.

- Contact Data [ITM.2] - Represents the processed environmental contact data.

- Threat Analysis Data [ITM.3] - Represents the processed contact data that has been identified as having hostile intent.

- Tracking Data [ITM.4] - Data that has been processed to provide tracking information for the engagement system.

- Engagement and Fire Control Data [ITM.5] - Data that has been processed and is an aggregate of tracking, characterization, and engagement priority data as well as data indicating autonomy status.

- Simulation Data [ITM.6] - Represents simulation data.

- System Status [ITM.7] - Represents system status for SUTRS.

- System Fault [ITM.8] - Represents system fault status for SUTRS.

- Engagement Status Message [ITM.9] - Terminal message from engagement system indicating status of engagement (active, terminated, ready).

- System Configuration Data [ITM.11] - Baseline System Configuration Data ROM used to determine system status on boot-up.

- COP Actionable Information [ITM.12] - Represents data and information that is actionable either by the operator, such as warnings and status, but also queries from and to the SUTRS operator to external systems.

Trigger Items

- Operator Input [EXT.ITM.6] -Represents the operator's input to the system. This trigger is input to Detect/Track Threat, Identify Threat, Engage Threat, Simulate Threat, and Display COP.

- Platform Availability Data [EXT.ITM.8] - Schedule availability of the host platform for maintenance. This trigger is input to Perform Maintenance Activities.

- Rules of Engagement [EXT.ITM.9] - Laws of Armed Conflict. This trigger is input to Engage Threat.

- Engagement and Fire Control Data [ITM.5] - Represents engagement and fire control data. This trigger is input to Simulate Threat.

- System Bootstrap [ITM.10] - Represents data cycling and System Boot checks to determine operational status upon system start-up. This trigger is input to Determine System Health Status.

D. ARCHITECTURE ANALYSIS

1. Discussion of CORESim® Results

a. OPSIT I

Figure 20 is a graphical representation of the CORESim® output of SUTRS Functions representing activities that would occur during Scenario I. In this simulation run, the SUTRS performs fifteen activities. The simulation executes without any anomalies.

The functions are executed sequentially and in parallel. The higher level SUTRS functions are executed sequentially and then repeated using a loop construct (iterative loop). This will be repeatedly executed in sequence until a preset domain value is reached; the routine then terminates normally and exits to the next functional activity.

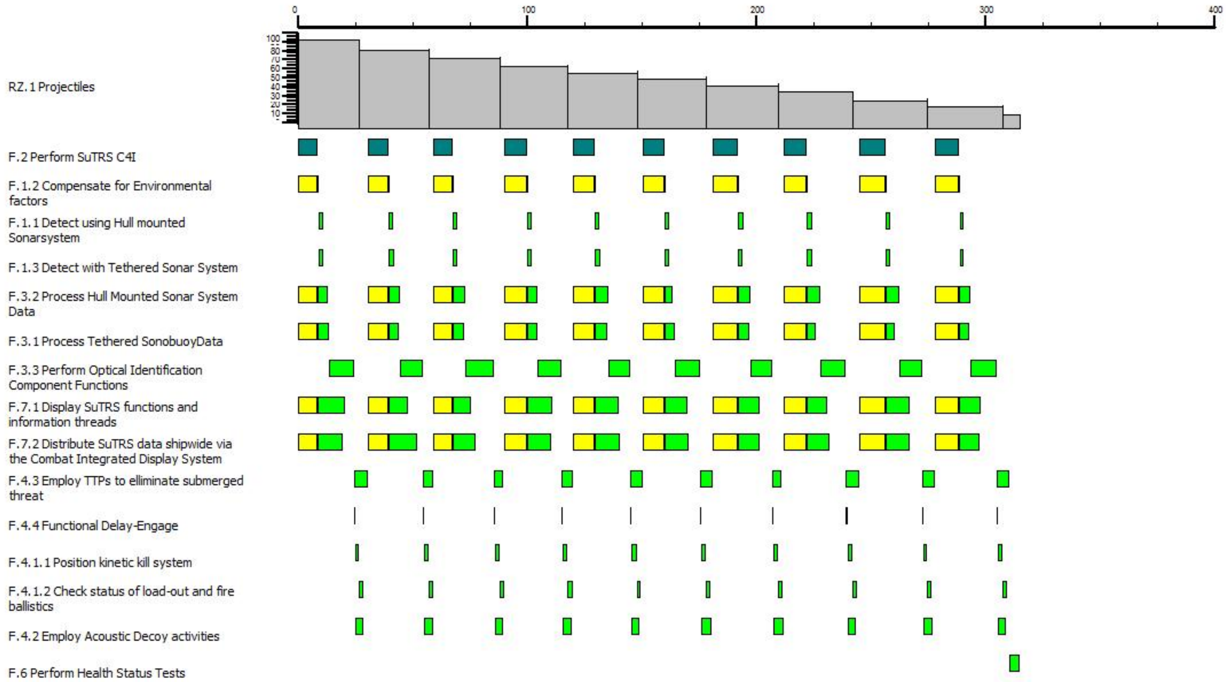

Figure 20. Case I CORESim® Results

b. OPSIT II

Figure 21 is a graphical representation of the CORESim® output of SUTRS Functions representing activities that would occur during the Training Simulation OPSIT II. In this simulation run, the SUTRS performs five activities. The simulation executes without any anomalies.

The functions "Display SUTRS Functions", "Distribute SUTRS data shipwide via the Combat Integrated Display system", "Perform SUTRS C4I" and "Perform Simulation and Training Activities" are executed sequentially. The "Determine System Health Status" is performed following the simulation activities.

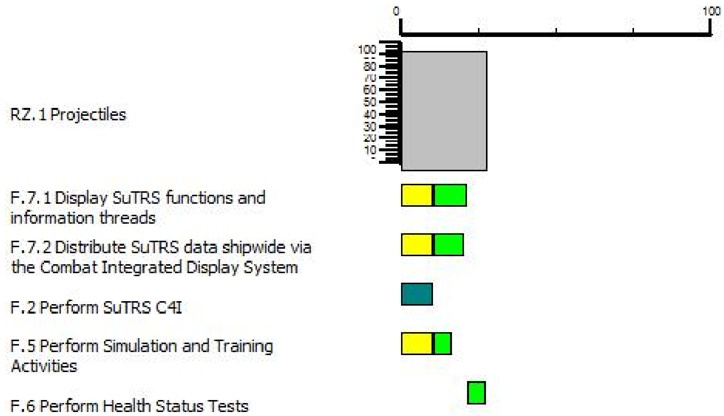

Figure 21. Case II CORESim® Results

In both OPSITs I and II, the functional activity names are listed in the column on the left. The dark green blocks correspond with activities that have no trigger. The light green indicates that the activity was triggered by outputs from another activity.

The CORE® architecture was modeled by placing both Scenario I & II activities in parallel with an "or" gate. When the CORESim® (simulation) is run on this model, the simulator generates a random number and selects the appropriate branch (either Scenario I or II). If we reset and run again, our results will vary since we are using a random number generator to select the appropriate branch.

The resulting time measurements reflect a SUTRS MOE—"Mean Time To Respond". Therefore, by simulating the architecture, we can identify any activities that are increasing the engagement timeline. The results of our simulation indicate that, in both Scenarios I and II, the cycle time to engage a sub-surface threat has a rough order of magnitude of ~30 seconds from detect to engage. The purpose of the timing window is to demonstrate an order of operations for the functional architecture. The timing parameters used preferred minimum time to respond for each functional step and each parameter used a statistical distribution to show the expected functional variability. Because no comparable technology currently exists, the actual viability of these parameters is an unknown and physically reasonable estimates for function delay intervals such as slew rate and time to fire were used. Depending on the model results, these values can be scaled based on the parameters of the final system configuration.

E. MODELING AND SIMULATION

The overall goal of the SUTRS Modeling and Simulation effort is to characterize the relevant attributes that impact the overall effectiveness of a generic MCM system. This is accomplished through the use of both a high level "Back of the Envelope" (BOE) calculation and a detailed simulation. The selection of meaningful input to the simulation is a critical step in this process. The QFD process provided a vehicle to determine what parameters are relevant to the project stakeholders. When combined with modeling and simulation a trade space can be established and used for architecture development.

1. Modeling Design and Assumptions

a. Back of the Envelope

In order to begin the modeling and simulation process, a BOE model was generated. The purpose of this model was to:

1. Create a graphical representation of the problem space,
2. To generate a symbolic mathematical characterization of the problem that could be used as a basis for future detailed models,
3. And, in general, to identify key assumptions early in the process.

For the purposes of threat response systems, the BOE model started with the following axioms:

1. A "response" must first be triggered by the presence of a "threat".
2. For any pair of surface platform and threat, there is a Closest Point of Approach (CPA)—a point at which the platform is as near to the threat as it can be without changing course.
3. A vessel with a linear distance to a mine that is less than the attenuation radius will cause the mine to detonate.

In addition to these axioms, the BOE model makes the following simplifying assumptions:

1. All threats are mines.
2. A “mine” threat’s depth is constant.
3. A surface vessel can only move in two dimensions.
4. The surface platform’s course and speed do not change (i.e., there is no acceleration).
5. The mine’s attenuation radius (i.e., the distance from mine to target at which the mine detonates) is equal to the mine’s blast radius.

With this set of assumptions, Figure 22 describes the orientation of a surface vessel and mine in 3-dimensional space as the surface platform approaches the mine along any approach vector.

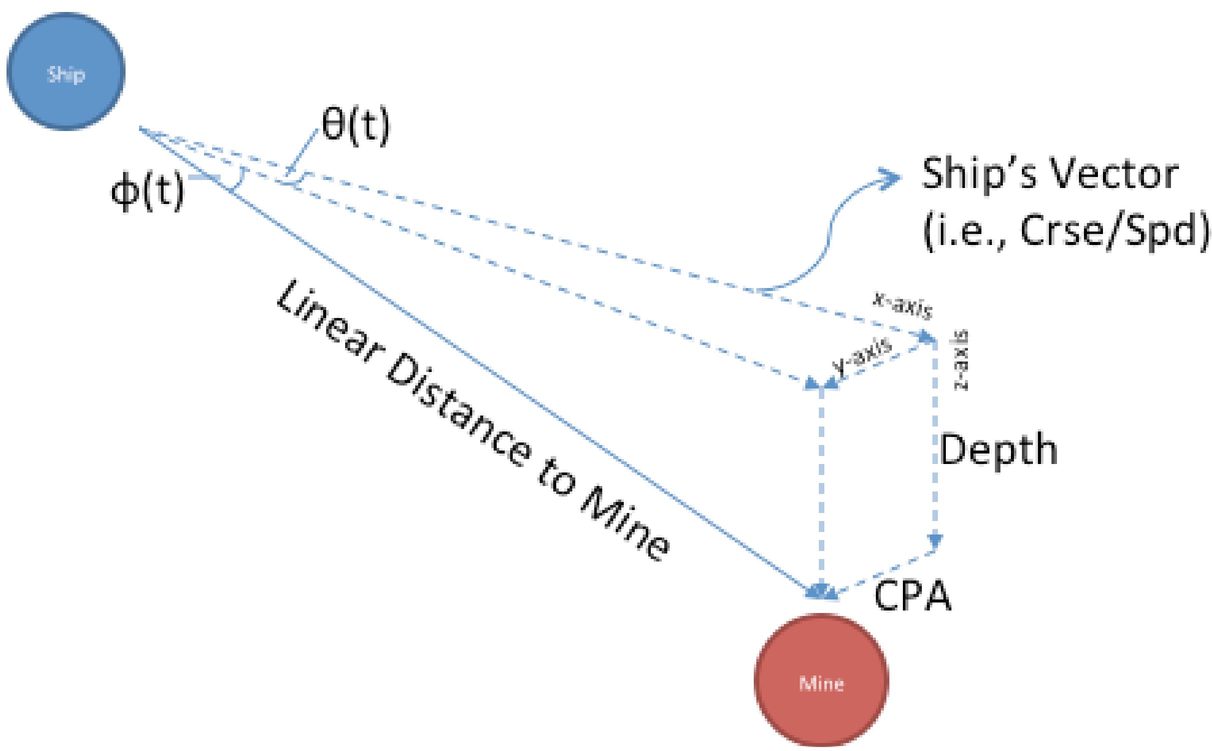

Figure 22. BOE Visualization

Note: this visualization’s orientation attempts to simultaneously express the linear distance to a mine threat in Cartesian and Radial coordinate systems.

It can be shown that the distance from the ship to the CPA along the ship's vector can be expressed as follows:

$$x(t) = x_0 - v * t \tag{1}$$

Where,

"x_0" is the distance from ship to CPA at time 0,

"v" is the ship's velocity, and

"t" is time.

Because x(t) is non-constant, the angle θ must also be a function of time. Equation 2 expresses θ as a function of time.

$$\theta(t) = tan^{-1} \frac{CPA}{x_0 - v * t} \tag{2}$$

Where,

"CPA" is a constant representing the closest point of approach.

Next, the ship's vector is converted into the 2-dimensional (i.e., on the surface) hypotenuse, which represents the distance to CPA as a function of time.

$$r(t) = CPA * sin\,\theta(t) \tag{3}$$

Substituting Equation 2 into Equation 3 results in the following:

$$r(t) = CPA * sin\left(tan^{-1} \frac{CPA}{x_0 - v * t}\right) \tag{4}$$

Now, having expressed the distance to CPA as a function of time, performing a similar operation in the z-plane which uses Depth as the constant resolves the radial distance from surface vessel to mine threat in 3-dimensions.

$$\varphi(t) = tan^{-1} \frac{Depth}{r(t)} \tag{5}$$

Substituting Equation 4 into Equation 5 results in the following:

$$\varphi(t) = tan^{-1} \frac{Depth}{CPA*sin\left(tan^{-1}\frac{CPA}{x_0-v*t}\right)} \tag{6}$$

Equation 6 is useful for fully characterizing the BOE model in 3-dimensions; however, it is unnecessary for completing the computation of the distance to the mine because r(t) and Depth fully characterize the total distance using the Pythagorean theorem.

$$f(t) = \sqrt{r(t)^2 + Depth^2} \tag{7}$$

Where

"f(t)" is the distance in 3-dimensions from the platform to the mine as a function of time.

Substituting Equation 6 into Equation 7 results in the following:

$$f(t) = \sqrt{\left(CPA * si\,n\left(tan^{-1}\frac{CPA}{x_0-v*t}\right)\right)^2 + Depth^2} \tag{8}$$

Thus, using Equation 8, if CPA, mine depth, initial velocity, and initial distance to CPA is known, the point-to-point distance from mine-to-platform can be calculated as a function of time. These calculations have been substituted into Figure 23 to produce the following graphical and mathematical BOE model.

Note: some intermediary calculations have been used for ease of use and readability.

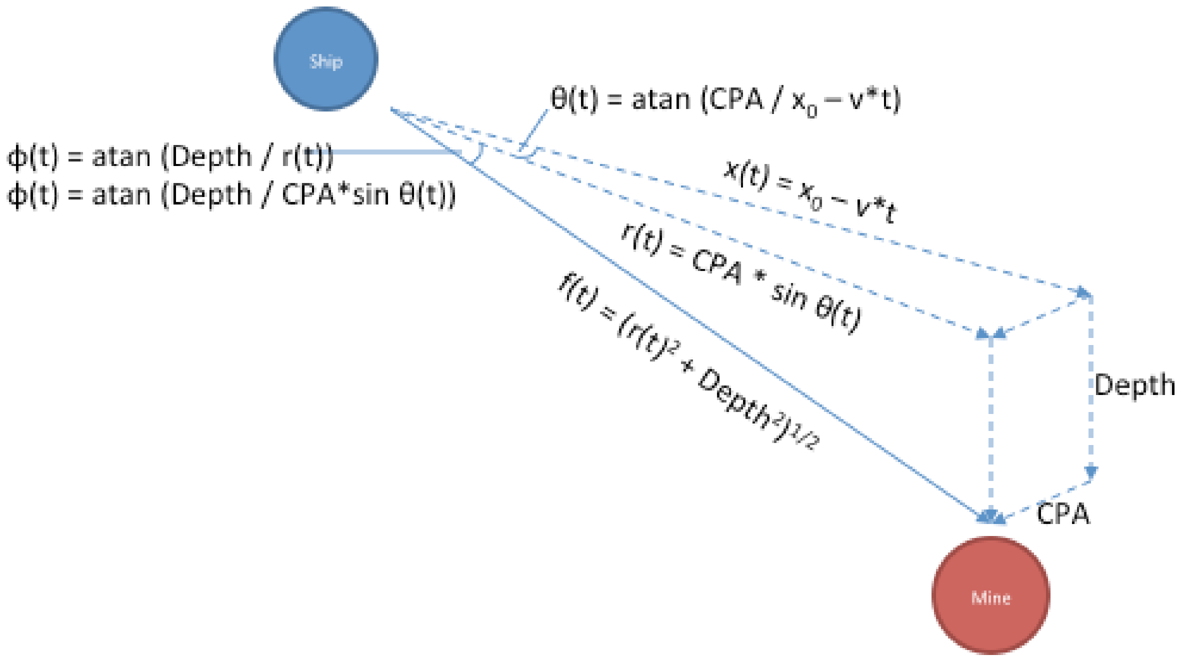

Figure 23. Graphical and Mathematical BOE Model

The importance of this graphical and mathematical model is that, given our axiom that a vessel within the radius of attenuation will cause a mine to detonate; we can use Figure 23 to determine whether a ship has "encountered" a mine. Thus, a model that compares linear distance to radius of attenuation (which has been assumed to be equal to the blast radius) was created in ExtendSim® and validated using Excel.

These models were the basis for the research described in this report. The results of those models are described in Section II.E.6.

b. Excel Simulation

Having established the BOE calculations that would be the foundation of more detailing simulation, SUTRS engineering team created a basic model of ship motion and mine triggering using Microsoft Excel®. The equations described in the previous sections were calculated, in a tabular format, using a *dt* of 1 second. These values were extended down through the spreadsheet as though the ship would approach and pass the mine in a straight line as illustrated in Table 9.

Table 9. Simulation spreadsheet headings

Time (s)	x-distance (m)	theta (deg)	cpa projection	Linear Distance(m)
0	400.000	4.358	2.316	401.166
1	387.653	4.496	2.389	388.857
2	375.307	4.643	2.467	376.550
3	362.960	4.800	2.551	364.246
4	350.613	4.968	2.640	351.946
5	338.267	5.149	2.735	339.648
6	325.920	5.343	2.838	327.354
7	313.573	5.552	2.949	315.065
8	301.227	5.778	3.068	302.780
9	288.880	6.023	3.198	290.501
Continued				

The formulas used in the distance calculations were linked to a table of constants (Table 10), enabling rapid changes of the values being modeled. Unit conversions were also applied.

Table 10. Simulation constants and conversion factors

Constants				
Speed	24	knots	**12.34667**	m/s
Initial Range	400	m	**400**	m
Mine Depth	100	ft	**30.48**	m
Blast Radius	300	ft	**91.44**	m
Detection Range	200	m	**200**	m
CPA	100	ft	**30.48**	m
Conversions				
knots to m/s	**0.514444**			
ft to m	**0.3048**			

Excel®'s conditional formatting function was employed to highlight the linear distances at which a mine was detected and/or triggered in yellow and red, respectively. This

visual dashboard display gave the SUTRS engineering team a quick representation of the order of magnitude of the effect of changes in model inputs. The output was used during detailed model design.

c. ExtendSim® Simulation

The concept developed in the initial model was refined and a more detailed simulation was constructed using ExtendSim® modeling software package. This tool allows a graphical block development of detailed simulations with detailed database input. ExtendSim®'s versatility was leveraged to create a realistic timeline for detection, and engagement/neutralization of a mine threat, in stride.

The basic functionality of the model was derived from a blend of the operational activities and system functions from the operational and system architecture.

The model simulates the ship moving at a rate of 5–20 kts approaching a mine. Modeling and Simulation efforts could have been conducted using CORE® and the architectures within that database; however, this is somewhat of a constraint of the model since some of the concepts of implementations are so diverse that they do not include some of the same system functionality. This however is not a limitation of the systems engineering process as these concepts are being evaluated in part by the model, but also in part by other methods that will account for the diversity.

2. Design of Experiments and Response Surface Models

a. Taguchi Methodology

The model has 9 inputs and each of these inputs can vary between a range of values. This makes choosing values to apply to each variable for a run of the model complex. Design of Experiment (DOE) concepts aid in creating input combinations that will show all of the interactions between variables after statistical analysis. One possible way to perform a design of experiment with a number of variables that each have multiple possibilities is to have as many runs as it takes to include all possible combinations; this is called a full factorial design (Information Technology Laboratory Homepage. N.p., n.d. Web n.d.). However, with 9 variables that each have 3 values, this would require 729 runs to test all possible combinations. The Taguchi Method is a way to

create a set of inputs that allows the experimenter to analyze all of the interactions between variables without requiring the large number of runs prescribed in a full factorial design (Fraley, et al. n.d.). Orthogonal arrays are used in the Taguchi Method to achieve the correct variability in the input combinations. A “Design of Experiments” (DOE) was used in the analysis of this project in the following subsections.

Table 11. Taguchi Model Variables

Attribute	Low	Med	High
Prob. Detection	0.2	0.5	0.8
Prob. Identification	0.2	0.5	0.8
Prob. Kill	0.2	0.5	0.8
Detection Range	100	500	2000
Engagement Range	50	200	500
Engagement Time	0.2	2	20
False Alarm Rate	0.1	0.2	0.3
Sensor Cycle Time	2	1	0.25
Approach Speed	5	10	20

Table 12. Taguchi Model from The University of York, N.p. 2004

Experiment Number	Prob. Dete	Prob. Ider	Prob. Kill	Detection	Engageme	Engageme	False Alar	Sensor Cy	Approach Speed
1	0.2	0.2	0.2	100	50	0.2	0.1	2	5
2	0.2	0.2	0.2	100	200	2	0.2	1	10
3	0.2	0.2	0.2	100	500	20	0.3	0.25	20
4	0.2	0.5	0.5	500	50	0.2	0.1	1	10
5	0.2	0.5	0.5	500	200	2	0.2	0.25	20
6	0.2	0.5	0.5	500	500	20	0.3	2	5
7	0.2	0.8	0.8	2000	50	0.2	0.1	0.25	20
8	0.2	0.8	0.8	2000	200	2	0.2	2	5
9	0.2	0.8	0.8	2000	500	20	0.3	1	10
10	0.5	0.2	0.5	2000	50	2	0.3	2	10
11	0.5	0.2	0.5	2000	200	20	0.1	1	20
12	0.5	0.2	0.5	2000	500	0.2	0.2	0.25	5
13	0.5	0.5	0.8	100	50	2	0.3	1	20
14	0.5	0.5	0.8	100	200	20	0.1	0.25	5
15	0.5	0.5	0.8	100	500	0.2	0.2	2	10
16	0.5	0.8	0.2	500	50	2	0.3	0.25	5
17	0.5	0.8	0.2	500	200	20	0.1	2	10
18	0.5	0.8	0.2	500	500	0.2	0.2	1	20
19	0.8	0.2	0.8	500	50	20	0.2	2	20
20	0.8	0.2	0.8	500	200	0.2	0.3	1	5
21	0.8	0.2	0.8	500	500	2	0.1	0.25	10
22	0.8	0.5	0.2	2000	50	20	0.2	1	5
23	0.8	0.5	0.2	2000	200	0.2	0.3	0.25	10
24	0.8	0.5	0.2	2000	500	2	0.1	2	20
25	0.8	0.8	0.5	100	50	20	0.2	0.25	10
26	0.8	0.8	0.5	100	200	0.2	0.3	2	20
27	0.8	0.8	0.5	100	500	2	0.1	1	5

3. Sensitivity Analysis

a. Data Extraction

Many different attributes were collected from the model; these include the range at which the object was detected, the range at which it was identified, the range at which it was engaged, and if it was not engaged successfully the range at which the mine detonated. Since the main objective of the SUTRS modeling and simulation program is to determine attributes that are relevant to the success of a mission, the key output that will be analyzed is whether or not the mine was engaged successfully. If it was not engaged successfully, then the mine would cause damage to the ship. Since we know that these mines are an asymmetric threat based on cost of a mine vs. the damage it is capable of doing, the output that counts the number of times damage is done to the ship is deemed to be most critical.

b. Main Effects

One of the most common and most effective ways of analyzing a Taguchi DOE is to produce Main Effects Plots (MEPs). This allows for graphical analysis which will identify the critical attributes relevant to the factor of whether or not the ship was damaged. Figure 24 shows the MEPs for the SUTRS enabled ship being damaged or not as it relates to all of the variables that were modeled. This does not include the parameters that were held constant throughout the modeling.

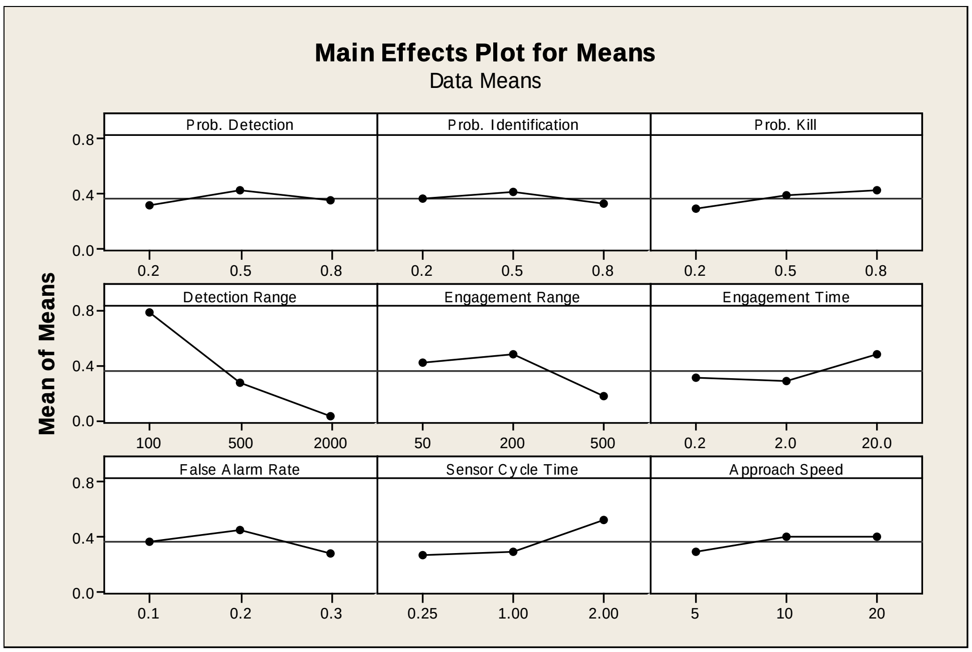

Figure 24. Main Effects Plot for Means

These attributes can now be described as:

- Probability of Detection

  Has some impact on the overall success of the mission, but the extent of which is unknown at this point since this only shows one attribute at a time. This does show that a system can be effective with a modest probability of detection as long as the sensor provides the capability for multiple opportunities for detection. Further discussion of the interactions of different attributes will be presented in the next section. This limitation in the modeling is not considered to be a negative aspect of the model; combinations of attributes will be explored in the next section so as to show the relationship between probability of detection and other variables.

- Probability of Identification

Has some impact on the overall success of the mission, but the extent of which is unknown due to conditions that cannot be modeled easily with the tools and methods used. This is similar to the situation that involves probability of detection. Due to the looping in the model, which allows for multiple opportunities to identify the object, there is a high likelihood that the object will be identified at some point. This minimizes the overall impact of probability of identification; however, it shows that a system can be effective with a low probability of identification as long as the system provides the capability for multiple identification opportunities.

- Probability of Kill

  Has a moderate impact on the overall success of the mission. It is clear that the probability of kill has a direct correlation to the overall success. This makes sense since depending on the maximum engagement range; the SUTRS may only have the opportunity to engage a target one time. If it can only engage one time it is absolutely critical that the probability of kill is very high.

  If the SUTRS has the opportunity to engage multiple times, either through the use of a long engagement range or high speed engagement system, it is very possible that a low probability of kill could be successful. The problem with this situation is that the cost of each engagement would go up since multiple engagements would be required. This will be discussed in more detail in later sections.

- Detection Range

  This is by far the most critical attribute. This is shown by the very steep curve in the MEP. This correlation is in line with all of the stakeholder conversations and resources that the SUTRS engineering team has seen. This makes sense since detection range is the first attribute in the linear engagement kill chain. Due to the high impact of this attribute, detailed discussion on interactions with other attributes will be in later sections.

- Engagement Range

  Has a critical impact on the overall success of the mission. The engagement range is very critical since the speed of engagement only allows for a limited number of engagements based on the maximum engagement range. When the engagement range is extended, more engagements are possible which leads to an improvement in mission success.

- Engagement Time

  Has minimal impact on the overall success of the mission. The time it takes to engage a target has a logical connection to the overall success of the mission since faster engagement times allow for the detonation of the mine at a longer distance, as well as more engagements if necessary. That being said, the results of the modeling and simulation show that the overall success of the mission is impacted only slightly when comparing shorter times to engage, but that high engagement times (i.e. 20.0 seconds) is not sufficient for the purposes of MCM operations in the manner in which they have been modeled.

- False Alarm Rate

  Has a minimal impact on the overall success of the mission. This is seen by the lack of a trend in the data. Logically, there is a point at which false alarm rate would have an impact, but for the range that was modeled, there was no significant impact. The true impact that a high false alarm rate would have on the overall success of the mission is the "shots fired" at benign targets. In a real world situation, the depth of the magazine (available "shots") would drive the requirement for false alarm rate, but due to the limitations in this model this type of analysis was postponed until a conceptual solution is identified.

- Sensor Cycle Time

  Has a significant impact on the overall success of the mission. This is shown by the distinct trend in the data. This makes sense since the lower the cycle time, the more chances the sensor has to detect an object. The more chances that SUTRS has to detect mines, the better the odds are to actually detect them; overall mission success follows based on this.

- Approach Speed

  Has moderate impact on the overall success of the mission. There is a distinct difference between the overall mission success for an approach speed of 5 and 10kts; there is less of a difference between 10 and 20kts. This shows that speeds below 10kts and preferably at or below 5kts will contribute to the overall success of the mission.

  There is a distinct tradeoff that is made with this. A slower approach time provides for an increased overall mission success, but then reduces the cycle time requirements for all other attributes. This is a commonly understood concept in the MCM world. In current operations, when a ship finds itself in a minefield they will come to a near complete stop until all supporting systems have a chance to identify and mitigate any and all targets. In the types of mission sets described in the SUTRS Design Reference Mission, time is a critical attribute and it is assumed in the modeling program that the ship is not willing to stop completely due to the urgency of their mission.

It is important to note that since this was a Taguchi DOE rather than a full factorial DOE this analysis is only done to a level at which the attributes can be described as having a major impact or minor impact. For true performance data for level of attribute and each combination a full factorial DOE would be conducted. This is not necessary for this type of analysis since the end goal of the SUTRS modeling and simulation program is to identify the attributes with a major impact on the overall mission success.

c. Response Surfaces and Attribute Interactions

Since many attributes were modeled in the SUTRS Modeling and Simulation (M&S) program it is critical to not only discuss the impact of individual attributes, but the interactions of multiple attributes. This interaction analysis provides for the identification of a technical trade space. For example, if sensor cycle time is increased, then probability of detection may be reduced. This and other examples will be discussed below.

(1) Interaction Plots. Since we know that some factors did not influence the overall success of the mission, based on the main effects analysis, these will be excluded from the interactions plot analysis. Since multiple attributes were identified to have some impact and there is a logical association between some of these attributes, these relationships will be explored to identify the tradespace between them.

The first example is the interaction between Sensor Cycle Time and Probability of Detection. The following figure shows the surface plot for these two attributes as they relate to the probability of the ship being hit by the mine.

From this point of view on the surface plot it is clear that the sensor cycle time must be below 1 second when combined with a relatively low probability of detection.

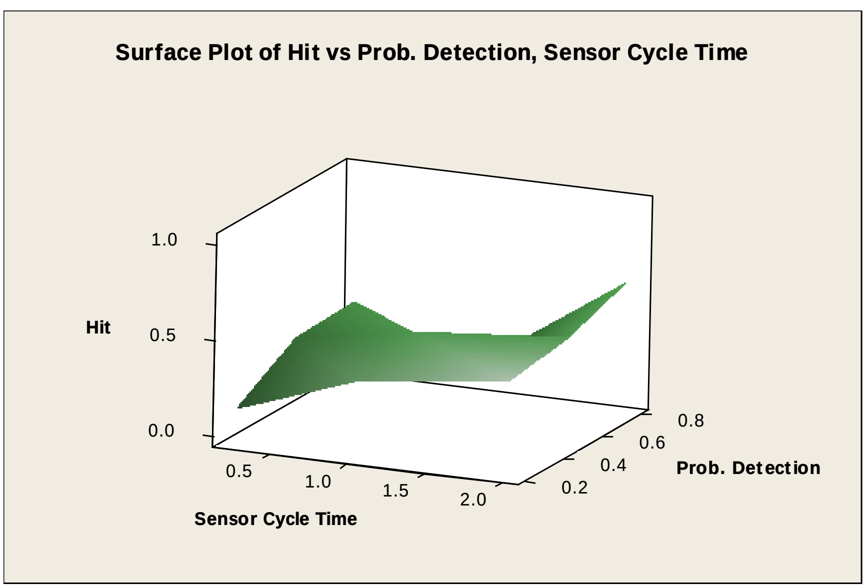

Figure 25. Surface Plot 1 (P(D) and Sensor Cycle Time

The following figure shows the same plot as Figure 25, but from a different angle.

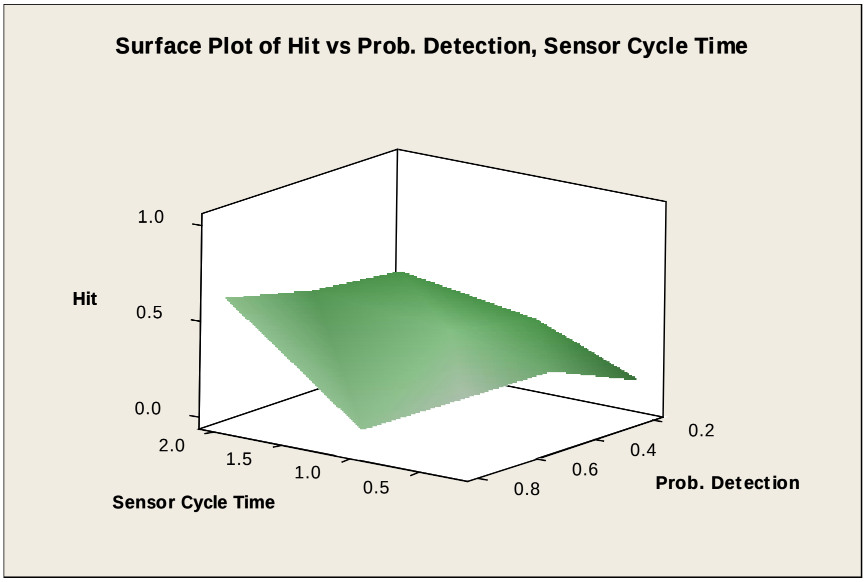

Figure 26. Surface Plot 2 (P(D) and Sensor Cycle Time)

From this point of view it is clear that a higher probability of detection will allow for slower sensor cycle rates. It also shows that at fast sensor cycle rates, the probability of detection is not nearly as important.

To explore this pairing further, a contour plot was generated and is shown in Figure 27.

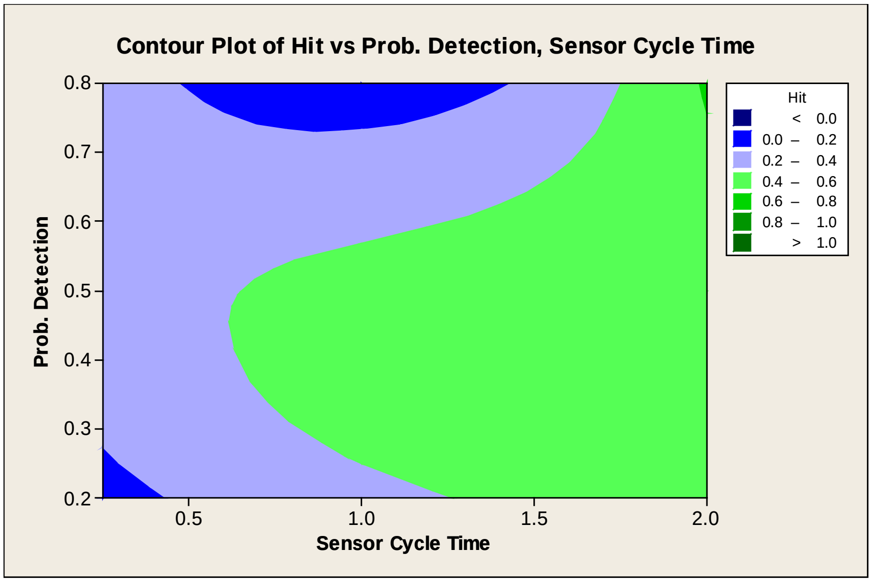

Figure 27. Contour Plot (P(D) and Sensor Cycle Time)

This contour plot shows the same data as the 3-Dimensional (3-D) surface plots above, but with a color coding to represent the different Z-axis values (the Z-axis refers to probability of being hit by the mine). This contour plot makes it absolutely clear that a high probability of detection is critical to mission success; it also shows that a relatively low probability of detection is acceptable when combined with a fast sensory cycle rate. For the following examples only a contour plot will be presented as it is the most effective at showing the overall attribute interactions.

The next example of attribute interactions is the interaction between probability of detection and probability of identification. The following figure shows a contour plot for probabilities of detection and identification as they relate to probability of being hit.

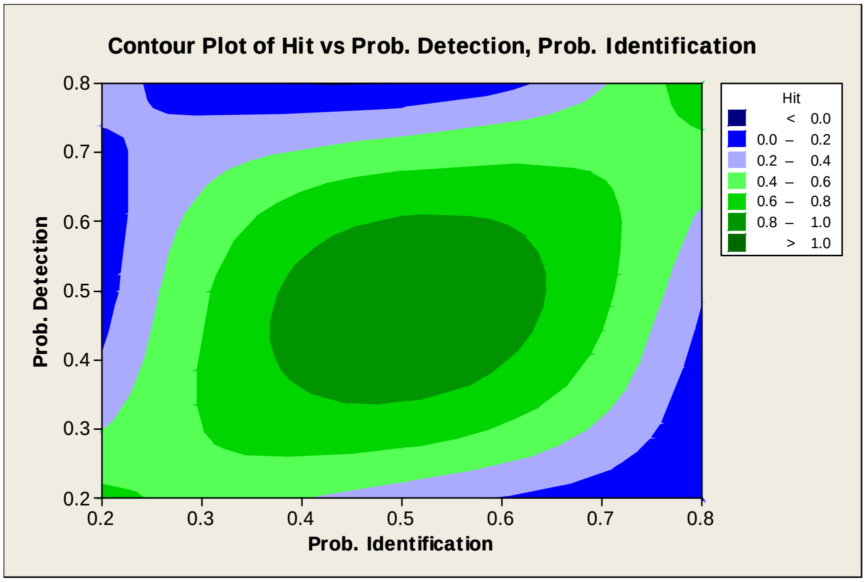

Figure 28. Contour Plot (P(D) and P(ID))

This contour plot shows that a relatively low probability of detection can be balanced by a high probability of identification and that a low probability of identification can be balanced by a high probability of detection. This makes sense since these are time sensitive cyclical attributes and the more cycles it takes to detect the object, the fewer opportunities the SUTRS will have to identify it.

One artifact of this plot that is not expected is the portion in the upper right corner where both probabilities are high. It was expected that this combination would lead to a low probability of the ship being hit. This artifact is attributed to the Taguchi DOE and that there is less data available at extreme combinations of attributes. Future modeling efforts should revisit this combination.

The following contour plot shows the interaction of Detection Range and Engagement Range as they relate to the probability of the ship being hit by the mine.

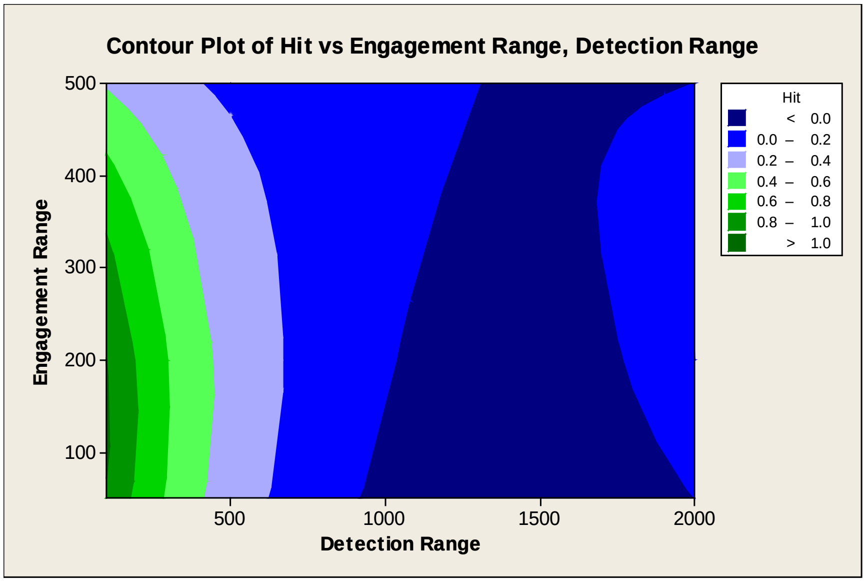

Figure 29. Contour Plot (Engagement Range and Detection Range)

This contour plot simply shows that as long as the detection range is significantly high that the engagement range can be relatively low. The opposite is not true. The SUTRS could not engage a target until it detects it.

The following figure shows the contour plot for Engagement Range and Engagement Time as they relate to the probability of the ship being hit by a mine.

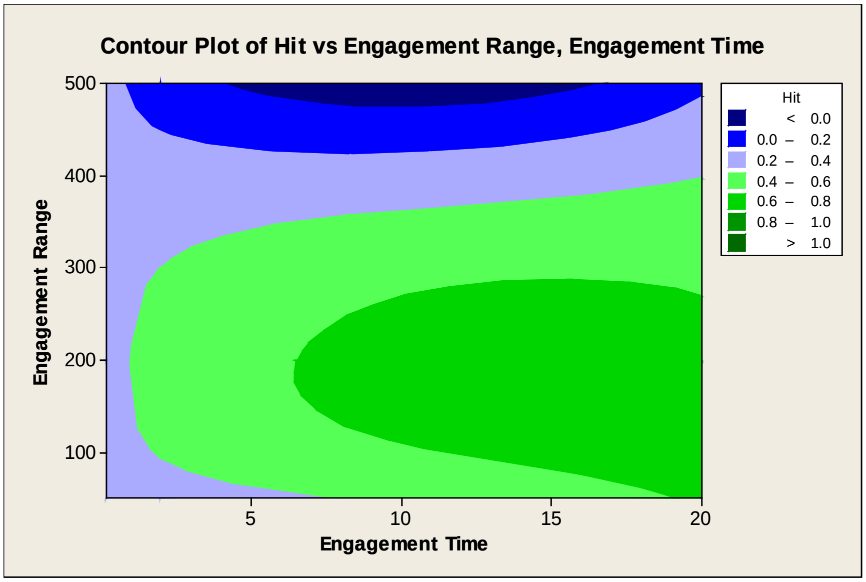

Figure 30. Contour Plot (Engagement Range and Engagement Time)

This contour plot shows that when combined, the engagement time is relatively insignificant as compared to the engagement range. This means that as long as a SUTRS solution can engage at a distance, the timeliness of the engagement is of minimal impact.

The following figure shows the contour plot for Engagement Time and Probability of Kill as they relate to the probability of the ship being hit by a mine.

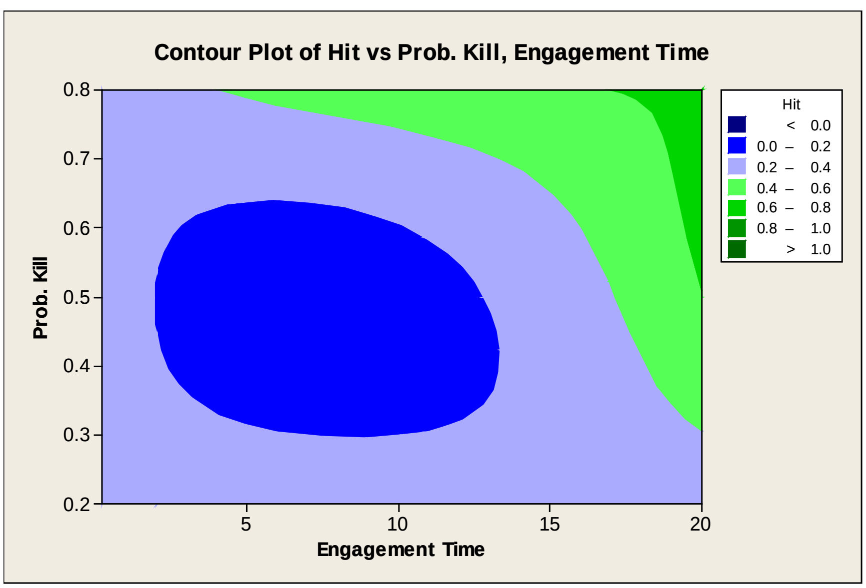

Figure 31. Contour Plot (P(K) and Engagement Time)

This plot shows that a moderate probability of kill could be acceptable when combined with a faster engagement time. This plot does not show a lower probability of being hit when the engagement time is low and the probability of kill is high; this is an unanticipated artifact of this modeling. This is attributed to the lack of data at the extreme attribute interaction pairings due to the Taguchi DOE.

The final example of attribute interaction is the combination of Detection Range and Approach Speed. This interaction is shown in Figure 32.

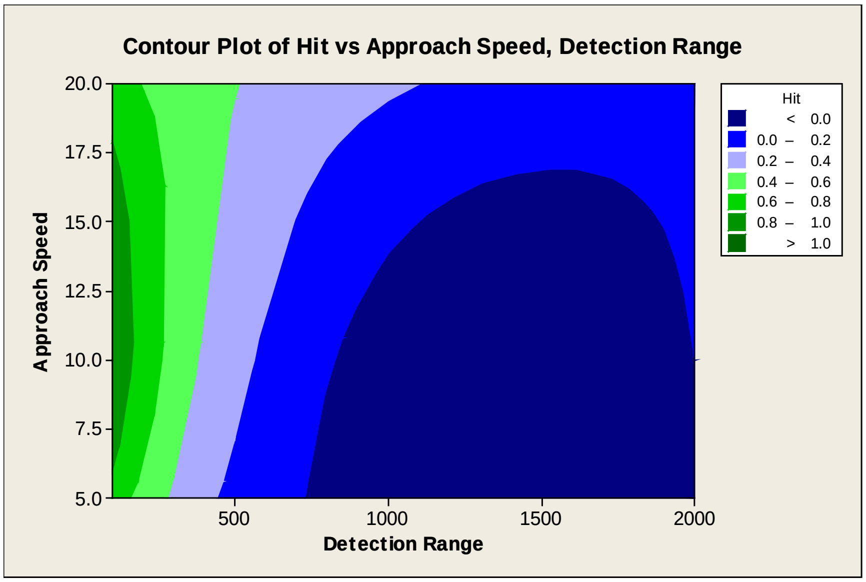

Figure 32. Contour Plot (Approach Speed and Detection Range)

This contour plot shows that as long as detection range is high, a ship should be able to proceed at a higher speed with minimal risk to the ship.

4. Discussion on Data Model Variability

The statistical nature of the MCM functions of Probability of Detection (P_d), Probability of Identification (P_i) and Probability of Kill (P_k) requires that the integrated model also demonstrate statistical variability in the mission success metrics. Both the ExtendSim® and CORESim® models have introduced statistical variance into the data model in the form of normal distributions and the following discussion elaborates on the central cause of the statistical variance.

a. Variability

According to Beasty (2007), the effectiveness of a piece of detection equipment can be represented by the discrete binomial probability distribution. The binomial distribution can only be applied to the detection of a mine as a single event, either successful or unsuccessful. For multiple events, the limit of the Binomial distribution as the number of events goes to infinity is the Poisson distribution, and using the theory of large numbers and Chebyshev's theorem, we can assume the limit of the Poisson distribution approaches the Normal distribution. It is the Normal distribution on which we will depend most heavily for the model simulation.

In the following section we discuss the justification and applicability of the probability distributions. The variability of P_d and P_i for a target is due to a number of factors that affect the functional capability of MCM detection and identification resources (Beasty 2007); (PEO (MUW) 2000).

Environmental Factors that affect detection and identification include but are not limited to the following:

- Water depth
- Bottom topography
- Bottom composition
- Reverberation
- Sea state
- Clutter (fish, detritus)
- Water clarity
- Water density
- Underwater obstacles
- Currents
- Climate and weather
- Temperature
- Salinity
- Conductivity
- Thermal layering

- Magnetic environment
- Background noise (acoustic neutrality)
- Pressure

Target physical factors that affect detection and identification include but are not limited to the following:

- Type of mine (bottom dwelling, moored, floating, buried)
- Size of mine
- Composition of mine
- Aspect angle and apparent aperture to detection equipment
- Performance factors of the detection equipment also contribute to the variability of detection and identification and include but are not limited to the following:
- Navigational errors
- Target Circular Error Probability (CEP)
- Twice Distance to target Root Mean Square Error

Each of these listed errors has a characteristic statistical distribution and these in turn have an accumulated effect on the Receiver Operating Characteristic Curve (ROC) that allows the mine hunter to discriminate between an actual target and a false positive indication (Fuller 2012). Because each of the listed factors has a characteristic distribution, and each of these distributions is convolved forming an aggregate distribution, we apply Chebyshev's theorem of statistical approximation to simplify the model assumptions and represent the aggregate distribution as a normal distribution.

5. Detection

Because current mine identification processes rely heavily on visual identification at close range, there are fewer variables that provide statistical impacts, but at a cost of time. As automated processes become more prevalent, the number of statistical variables and their impact will increase. This section will focus on the statistical variability of mine detection as it relates to sonar.

According to Thompson and Bell (1997), an average signal to noise energy ratio (SNR) of approximately 12 dB is desired to adequately discriminate a target of interest from the background noise and signal variation generated by the various factors listed above.

The 2-way sonar equation is similar in form to the 2-way radar equation (Minkoff 2002). If the confounding factors are accumulated as Noise (Nc), and the energy of the return signal from the mine-like object is Ms, we have in equation form:

$$SNR\ dB = 10 \log\left(\frac{Ms}{Nc}\right) \tag{9}$$

$$Ms = \frac{Pt * Gt * v^2 * \varphi}{(4\pi * R)^2 * f^2} \tag{10}$$

Where:

Ms: Mine return signal power	*Nc: Accumulated noise power*	*φ: mine cross-sectional aperture factor*
Pt: Sonar Transmitter power	*Gt: gain of transmitter aperture*	*Gr: gain of receiver aperture*
R: Range from mine	*v: velocity of sound underwater*	*f: frequency of the transmitted signal*

$$Nc = F\ (Nd, P, T, Nm, Ds, \ldots) \tag{11}$$

Where:

Nd: Environmental noise at depth	P: Underwater pressure	T: Water Temperature
Nm: Magnetic Noise	Ds: Specific density of water	…: others

6. Two Sphere Model

Detection in sonar world is a complex function that in its basic form includes parameters of wavelength, power, sonar cross section or apparent aperture of the target, and apparent aperture or gain of the receiver. Apparent aperture and distance from target can add non-linearly to power transmitted reflected and received. We can imagine the statistical interaction between a detection system such as sonar, and a mine-like object, by developing a simple 2-sphere model. Such a model allows us to visualize the effects of range, target aperture size, and noise.

Looking at Figure 33 we will represent the sonar system as being at the center of sphere- 1 and the target or mine-like object as the center of sphere-2. The radius of sphere-1 is the maximum detection range of the sonar as described by equation (1). The radius of sphere-2 corresponds to the effective aperture of the target.

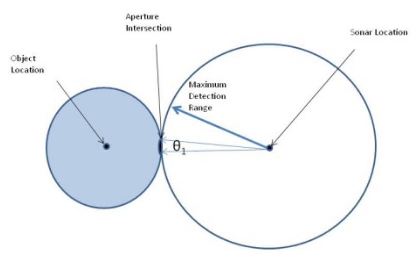

Figure 33. Sonar System at Center

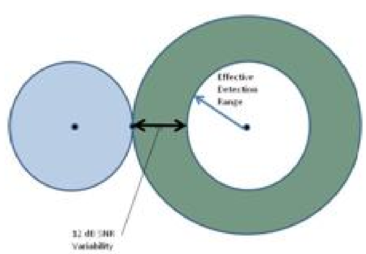

Figure 34. Range Reduction

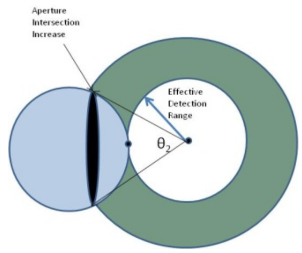

Figure 35. New Effective Range

The intersection of the two spheres represents the effective detected aperture of a target. The detection range of the sonar represented by sphere-1 will exhibit statistical variability due to the environmental factors listed above.

The effective aperture of the target represented by sphere-2 will exhibit statistical variability due to the target physical factors listed above. It is important to note that frequency resonance of an object is a multiple of the half-wavelength of sound as opposed to the quarter-wavelength of an electromagnetic aperture. The target aperture will also exhibit statistical variability due to the environmental factors listed above but we can assume for the simplified model that this variability can be included in the variability exhibited by sphere-1.

The minimum intersection between two spheres of any size is a point. This is the absolute maximum detection range for our model but may not be within a detection threshold. Detection threshold corresponds to the ratio of the surface area of intersection to the surface area of sphere-1. The area of intersection is approximately {cosine (θ_1/2) x θ_1} steradians.

From (Thompson and Bell 1997), we desire an SNR of approximately 12 dB. In order to gain this level of increase in a static environment, we would need to reduce our range to target by one-half (Minkoff 2002). This reduction in range is depicted in Figure 34 In order to regain the minimum area of intersection; the target sphere must be moved inside the maximum range until it intersects the new effective range depicted in Figure 35. The effective area of intersection for the maximum range is now {cosine (θ_2/2) x θ_2} steradians. Because of the non-linear nature of the cosine function, the difference in the

ratio of aperture areas to maximum detection area can be quite significant and actual the detection threshold of a mine-like object can fall anywhere between these values depending on the characteristic environment.

The key lesson to be drawn from this discussion is that the probability of detection of a mine-like object is a sliding variable that has values from 0.00 to 1.00 and that depends on many factors outside of the control of the mine hunter. It is both insufficient and incorrect to state that the probability of detection will be a fixed value. Our models therefore correctly incorporate an approximation of this variability vice using a fixed value.

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IV. ANALYSIS OF ALTERNATIVES

A. ANALYTICAL HIERARCHY PROCESS

The SUTRS Engineering Team selected the AHP as an aid to determine a preferred system configuration during the Analysis of Alternatives (AoA). The AHP process utilizes a weighting system based on verbal declaratives instead of operational metrics for Operational Measures of Effectiveness (OMOE)s. (Martens and Rempel 2010) (Hootman and Whitcomb 2005)

The rationale for taking this approach is that the system proposed (1) does not currently exist in any form; and (2) the system will require an investment in either developing new technologies or enhancing existing technologies. Because of these factors, no hard metrics are currently available that might be utilized for the development of a deterministic OMOE.

The AHP process was facilitated through the use of modeling within CORESim® and ExtendSim®. The CORESim® model was able to produce a scalable event timeline that demonstrated the use of series and parallel operation functions that provided insight into the flow of activities and could be used to indicate where time sequences needed to demonstrate efficiency gains. These models are described in Section III of this report. For example, the identification time increment is the source of significant lag in the kill chain and is identified as an area where technology needs significant development. The ExtendSim® model was able to incorporate statistical parameters of platform performance relative to subsystem performance in order to determine the dependence sensitivity. This provides insights into the minimum required engagement ranges, detection ranges, and factors of mission speed that must be considered in the AoA.

There are many MCM components in the fleet today and others that are in the acquisition process. The technologies fall into a couple of families: detection, mine hunting, mine sweeping, and platforms that can be equipped with different components depending on the needs of the mission. The following charts list some of the programs in MCM today.

Table 13. Mine Detection

System Number	Name	Provider	Notes	Platform
AN/AQS-20	Minehunting Sonar System	Raytheon	Towed side scan sonar	MH-60S (Jane's Underwater Security Systems and Technology 2007)
AN/AQS- 24	Airborne Minehunting Sonar	Northrop Grumman	Towed laser and side scan sonar	MH-53 (Jane's Underwater Security Systems and Technology 2007)
AN/AES-1	Airborne Laser Mine Detection	Northrop Grumman	Towed laser sensor	MH-60S (Jane's Electro-Optic Systems 2012)
AN/SQQ-32	Minehunting Sonar	Raytheon	Hull-mounted detection and classification sonar	Avenger Class Ships (Jane's Underwarer warfare Systems,. 2012)
AN/BLQ-11	Long Term Mine Reconnaissance System	Boeing	RF and Sonar sensors, UUV launched from submarines	Submarines (Jane's Underwater Security Systems and Technology 2008)
	Surface Mine Countermeasure Unmanned Undersea Vehicle (SMCM UUV) 'Knifefish'	General Dynamics and Bluefin Robotics	UUV with detection capabilities in high clutter environment, fully autonomous and does not send data until it is back to ship	Ship-based (Jane's Navy International 2012)
AN/DVS-1	Coastal Battlefield	Arete	“detection and	FireScout

System Number	Name	Provider	Notes	Platform
	Reconnaissance and Analysis (COBRA)	Associates	localization of minefields & obstacles in the surf zone and beach zone prior to an amphibious assault”	(United States Fact File 2011)

Table 14. Mine Hunting

System Number	Name	Provider	Notes	Platform
AN/AQS-235	Airborne Mine Neutralization System	Raytheon	Releases BAE Archerfish expendable UUVs; retargets the mine and destroys mine with warhead	MH-60S (Jane's Navy International 2011)
AN/AQS-232	Airborne Mine Neutralizing System	Raytheon	(larger version of AN/AQS-235 for MH-53E helicopter)	MH-53 (Jane's Underwater Warfare Systems 2011)
AN/AWS-2	RAMICS	Northrop Grumman	Gun used for near-surface mine destruction	MH-60S (Jane's Underwater Warfare System 2011)

Table 15. Mine Sweeping

System Number	System Name	Provider	Notes	Platform
AN/SLQ-37	Influence Mine-sweeping System		Acoustic and magnetic sweep	Avenger Class (PEO LCS n.d.)
AN/SLQ-38		General Dynamics	Mechanical sweep for moored mines	Ship-based
AN/ALQ-219	Shallow Water Influence Minesweep System	ITT Electronic Systems, Thales	Acoustic and magnetic sweep	MH-53E (Jane's Underwater Warfare Systems 2011)

System Number	System Name	Provider	Notes	Platform
	Modular Open Loop System	ITT Electronic Systems	Acoustic and magnetic sweep	Ship-based (GMB USA 2009)
AN/ALQ-220	Organic Airborne and surface influence sweep (OASIS)	ITT Electronic Systems	Acoustic and magnetic sweep	MH-60S (Jane's Underwater warfare Systems 2011)
	Unmanned Surface Sweep System (US3)	ITT Electronic Systems	Acoustic and magnetic sweep	USV (Jane's Underwater Warfare Systems 2011)

Table 16. Unmanned Platforms Used with MCM Systems

System Name	Provider	Notes	Platform
Unmanned Surface Vehicle (USV)	Oregon Iron Works	Unmanned 11m rigid-hull inflatable boat, equipped with US3	Released and controlled from Ship (International Defense Review 2012)
Remote Multi-Mission Vehicle (RMMV)	Lockheed Martin	"unmanned, autonomous semi-submersible, high endurance, low-visible system", diesel powered	Released and controlled from Ship (United States Navy Fact File 2011)
MQ-8B FireScout	Northrop Grumman	Helicopter UAV that can be equipped with various sensor systems	Released and controlled from Ship (Defense Industry Daily 2012)

Mine countermeasure missions have traditionally been undertaken by a dedicated group of MCM vessels. There are 14 Avenger class MCM ships in the fleet today and have home ports in San Diego, CA., Japan, and Bahrain. (United States Navy Fact File 2012) (Commander Naval Surface Force, U.S. Pacific Fleet n.d.) The Avenger class is capable of both mine-hunting and mine-sweeping. If the ships are required by the fleet

away from their home-port they are transported by container vessel to the mission area (Commander Naval Surface Force, U.S. Pacific Fleet n.d.). This causes huge delays in responding to real or potential threats. The Avenger Class MCM ships are equipped with SLQ-37, SLQ-38, SLQ-48, SQQ-32 mine detecting, hunting, and sweeping technologies (Jane's Underwater Warfare Systems 2012). The newest addition to the Navy MCM strategy is the MCM mission module for the Littoral Combat Ship, LCS. The central idea behind the LCS is its mission modules. There are three mission modules currently in development: Surface Warfare (SuW), MCM, and Anti-submarine Warfare (ASW). (International Defense Review 2012) Every LCS ship will be equipped with a mission module depending on the mission/situation. The mission modules will be easily exchangeable even in a forward location. (Jane's Navy International 2011). For example an LCS ship will be able to exchange their SuW mission module to a MCM module if mines are a threat in their environment. The MCM module will include the systems listed in Table 17.

Table 17. System in LCS MCM Mission Module (International Defense Review 2012)

System	Quantity
USV (with USSS)	1
RMMV	2
AN/AQS-20A	3
MH-60S (with OASIS, AMNS, ALMDS)	1
Fire Scout VTUAV (with COBRA)	1
Knifefish (expected delivery 2017)	1

This mission module gives the LCS the capabilities to search, sweep, and hunt from the air, the water, and underwater. These technologies include a wide range of MCM approaches but it is far from constant "in-stride" detection and avoidance/removal. The LCS mission module is a huge step from the limited number of dedicated MCM ships that has been standard for the Navy for decades. The first complete MCM mission

module has an expected delivery date of February 2013, unless otherwise noted and will be followed by future increments in technology and system development (International Defense Review 2012) (Jane's Navy International 2011).

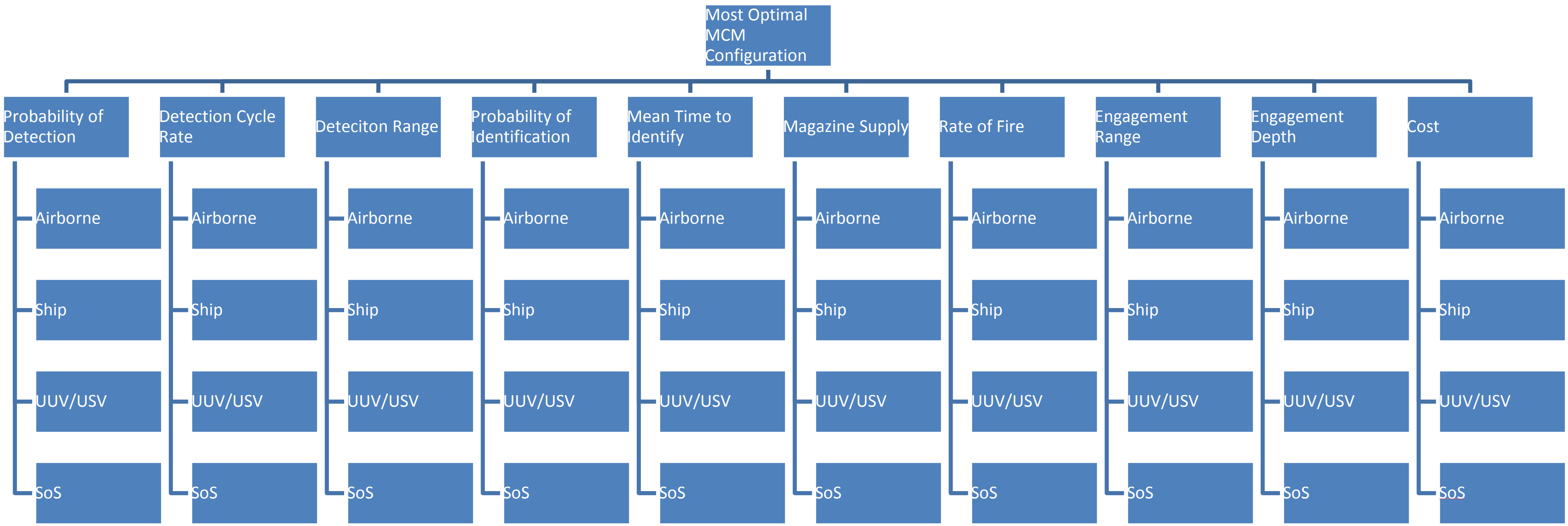
1. CORE®ExtendSim®

Based on this research, there are currently 4 basic MCM technology configurations; 1) Airborne MCM, 2) Ship-based MCM, 3) Unmanned Surface/Underwater Vehicles, and 4) Organic System of Systems which utilizes an optimized combination of the other three independent configurations. In order to determine the most operationally feasible MCM configuration or alternative, the team decided to use the AHP. AHP is a method used by decision makers to determine the relative importance of attributes, and also to compare how well the options perform on the different attributes (Wright 2009).

AHP provides a means of converting qualitative attributes into quantitative scores, which are then used to conduct 1-to-1 pair-wise comparisons between incrementally selected configuration options. Since this analysis utilized UNCLASSIFIED sources to research these MCM technologies, specific performance metrics, capabilities, and limitations data were either very limited or non-existent. This lack of data forced the SUTRS analysis team to correlate open source commentary regarding the various MCM systems to develop an aggregate understanding the capabilities of each of these four basic configurations in order to score each of them against the MCM performance criteria established during the SUTRS mission analysis.

The first step of the AHP is to decompose the decision space into the three basic levels of a decision hierarchy; 1) Goal(s), 2) Decision Criteria, and 3) Alternatives. The hierarchy in Figure 36 represents how each alternative configuration can be independently assessed against each MCM performance criteria. This approach allows for a very complex and dynamic decision space to be analyzed in a much more simplified pair-wise manner.

Figure 36. SUTRS AHP Decision Hierarchy



As is the case with many multi-objective decisions, the SUTRS optimization analysis was conducted using qualitative and subjective input for each configurations performance relative to the performance criteria. The following verbal-to-value scoring scale was adapted from the fundamental scale of absolute numbers corresponding to verbal comparisons mentioned in the previous section (Section III.A) to develop the quantitative rank within each AHP:

Table 18. SUTRS AHP Verbal-to-Value Scoring Scale

Very Poor	1
Poor	3
Fair	5
Good	7
Very Good	9

These scores were then applied to the various alternatives relative to performance metrics in Table 19. The verbal scores applied to each basic MCM alternative are the result of an aggregate understanding of the current MCM technologies identified by the SUTRS MCM technology research effort.

Table 19. SUTRS AHP Verbal Scoring

	Probability of Detection	Detection Cycle Rate	Detection Range	Probability of Identification	Mean Time to Identify	Mean Time to Respond	Magazine Supply	Rate of Fire	Engagement Range	Engagement Depth	Cost per Engagement
Airborne MCM	Fair	Good	Fair	Fair	Good	Very Good	Good	Good	Poor	Very Poor	Fair
Ship Based MCM	Good	Fair	Good	Good	Good	Good	Good	Fair	Good	Fair	Good
USV/UUV	Good	Good	Good	Fair	Fair	Good	Poor	Fair	Good	Good	Fair
Airborne/Ship based/Unmanned SoS	Very Good	Good	Good	Good	Good	Very Good	Very Good	Fair	Good	Good	Very Good

Pair-wise comparison matrices were then developed for each attribute in order to compare and contrast the alternative MCM configurations to each other. After the

alternatives are compared to each other relative to the attributes, the performance scores are normalized and combined in Table 20. The weights for each attribute are then retrieved from the QFD 2 in order to weigh each alternative. This final weighting ensures that the stakeholder's input is used to rank the alternatives.

Table 20. AHP Conclusion - Preferred MCM Configuration

	Probability of Detection	Detection Cycle Rate	Detection Range	Probability of Identification	Mean Time to Identify	Mean Time to Respond	Magazine Supply	Rate of Fire	Engagement Range	Engagement Depth	Cost per engagement	Final weighted Results
QFD Weighting	**0.084**	**0.066**	**0.079**	**0.070**	**0.065**	**0.093**	**0.025**	**0.030**	**0.072**	**0.065**	**0.100**	
Normalized weighting	**0.112**	**0.088**	**0.105**	**0.094**	**0.087**	**0.124**	**0.033**	**0.040**	**0.096**	**0.086**	**0.133**	
Airborne MCM	0.179	0.269	0.192	0.208	0.269	0.281	0.269	0.318	0.125	0.050	0.278	0.217
Ship Based MCM	0.250	0.192	0.269	0.292	0.269	0.219	0.269	0.227	0.292	0.250	0.389	0.271
USV/UUV	0.250	0.269	0.269	0.208	0.192	0.219	0.115	0.227	0.292	0.350	0.278	0.252
SoS	0.321	0.269	0.269	0.292	0.269	0.281	0.346	0.227	0.292	0.350	0.056	0.260

According to the Final Weighted Results, the Ship Based MCM configuration represented the most optimized MCM configuration based on current MCM capabilities and value placed on various performance attributes by MCM stakeholders.

B. SENSITIVITY ANALYSIS

The modeling and simulation results described in this report were subject to the limitations and constraints described in Section III.E.4. In order to assess to what degree the impacts of those limitations and constraints might confound the results of the research described in this report, a sensitivity analysis was performed on each of the parameters used in the model.

The weight at which a system preference changes is computed using slope equations.

$$y = mx + b \tag{12}$$

Where

"y" is the overall AHP score given the changed weight.

"x" is the parameter's weight (which for the sensitivity analysis will be either 0 or 1)

"b" is the AHP score at x = 0.

"m" is the slope of the line.

$$m = \frac{y_1 - y_0}{x_1 - x_0} \tag{13}$$

Substituting 1 and 0 into the equation for the values of x, Equation 14**Error! Reference source not found.** transforms to…

$$m = y_1 - y_0 \tag{14}$$

And finally, in order to calculate the x-value of the intersection point—a point where the y-values of two alternatives is equal— Equation 14 is used, which is derived as follows:

$$y_1 = y_2 \tag{15}$$

Substituting Equation 15**Error! Reference source not found.**…

$$m_1 x + b_1 = m_2 x + b_2 \tag{16}$$

Isolating "x" on one side of the equality…

$$b_1 - b_2 = m_2 x - m_1 x \tag{17}$$

And finally, solving for "x"…

$$x = \frac{b_1 - b_2}{m_2 - m_1} \quad (18)$$

The results of that sensitivity analysis are described in this section.

1. Probability of Detection

Figure 37 indicates that the preference of systems shifts from Ship Based MCM to a SoS approach at a weight of 0.393. Given the current weight of 0.084, this would constitute a 369% increase in weight.

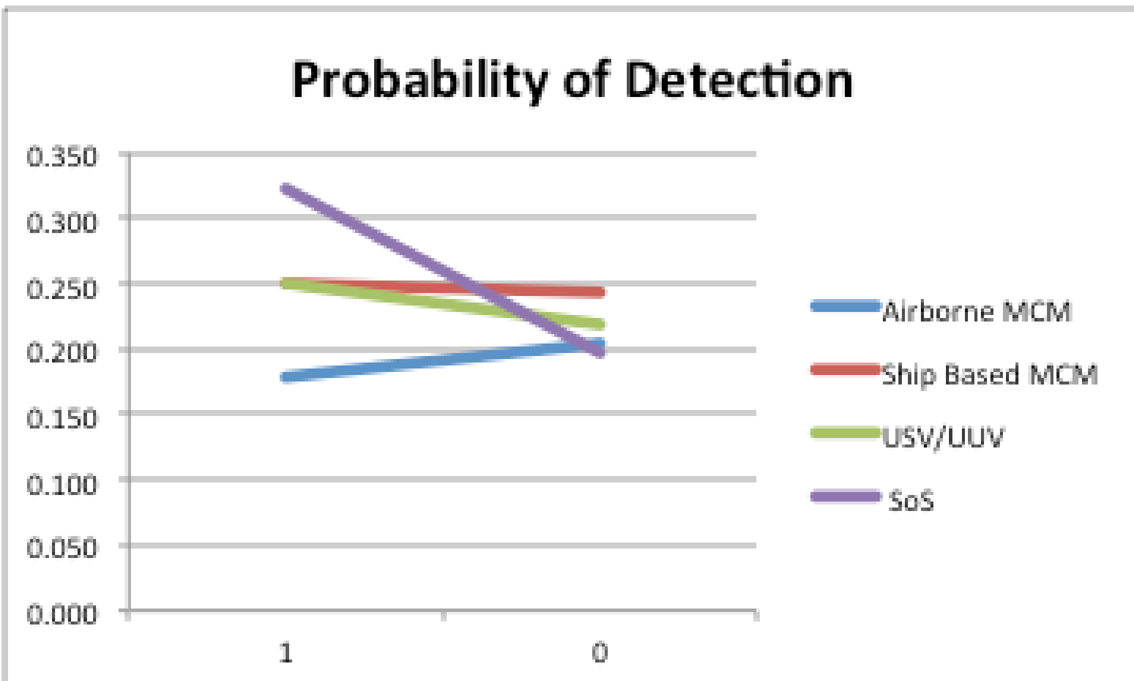


Figure 37. Probability of Detection

2. Detection Cycle Rate

Figure 38 indicates that the preference of systems shifts from Ship Based MCM to a SoS approach at a weight of 0.393. Given the current weight of 0.066, this would constitute a 375% increase in weight.

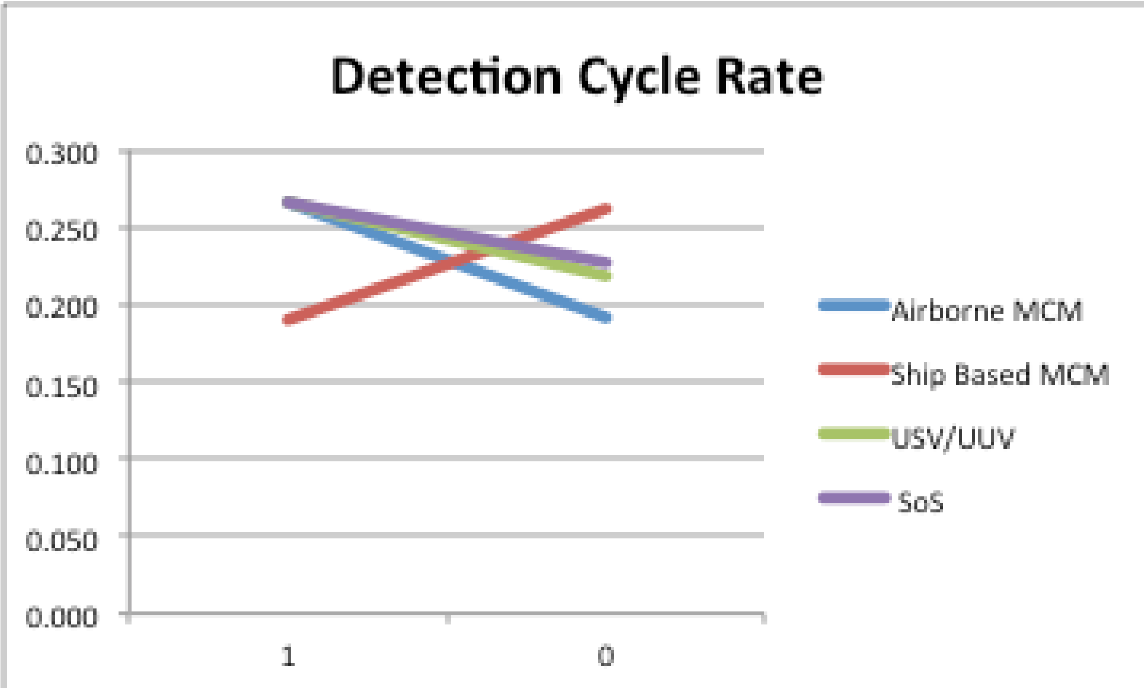


Figure 38. Detection Cycle Rate

3. Detection Range

Figure 39 indicates that the preferred alternative is insensitive to Detection Range.

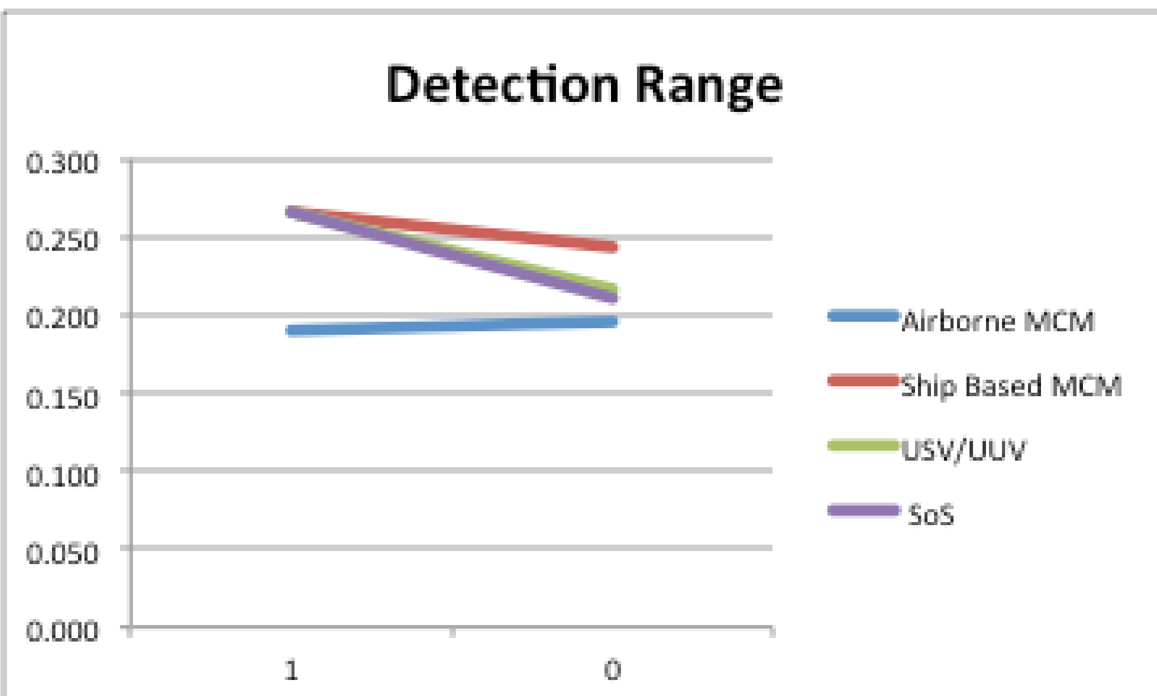


Figure 39. Detection Range

4. Probability of Identification

Figure 40 indicates that the preferred alternative is insensitive to Probability of Identification.

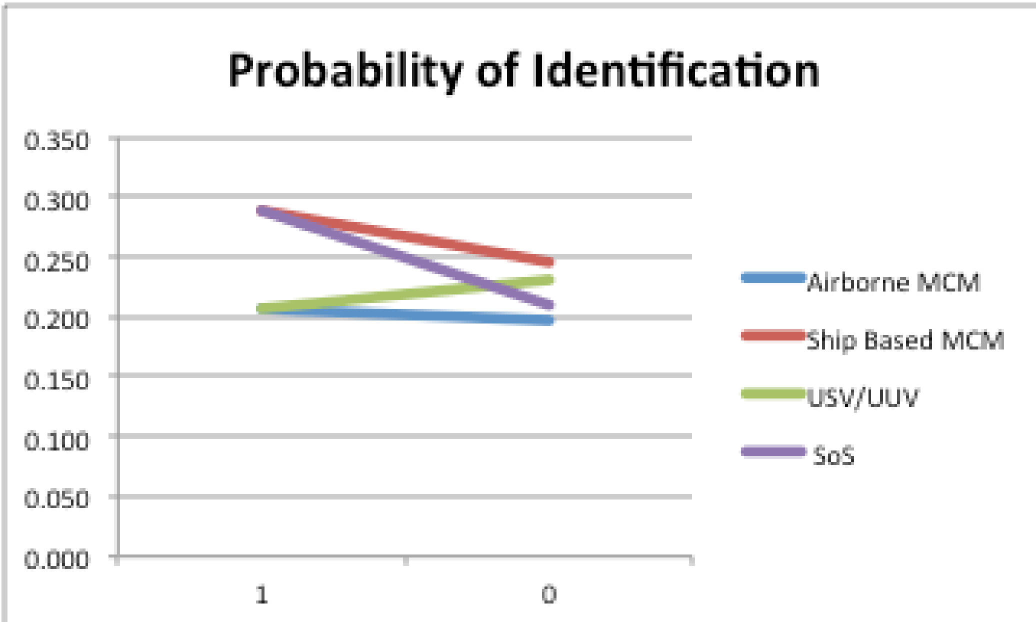


Figure 40. Probability of Identification

5. Mean Time to Identify

Figure 41 indicates that the preferred alternative is insensitive to Mean Time to Identify.

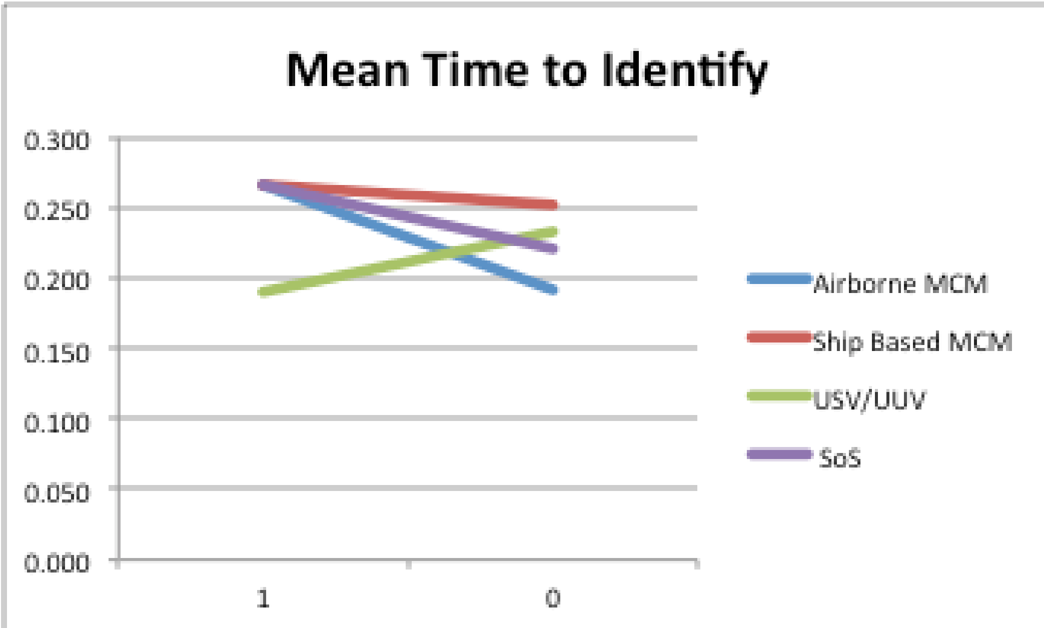


Figure 41. Mean Time to Identify

6. Mean Time to Respond

Figure 42 indicates that the preference of systems shifts from Ship Based MCM to a SoS approach at a weight of 0.393. Given the current weight of 0.093, this would constitute a 322% increase in weight.

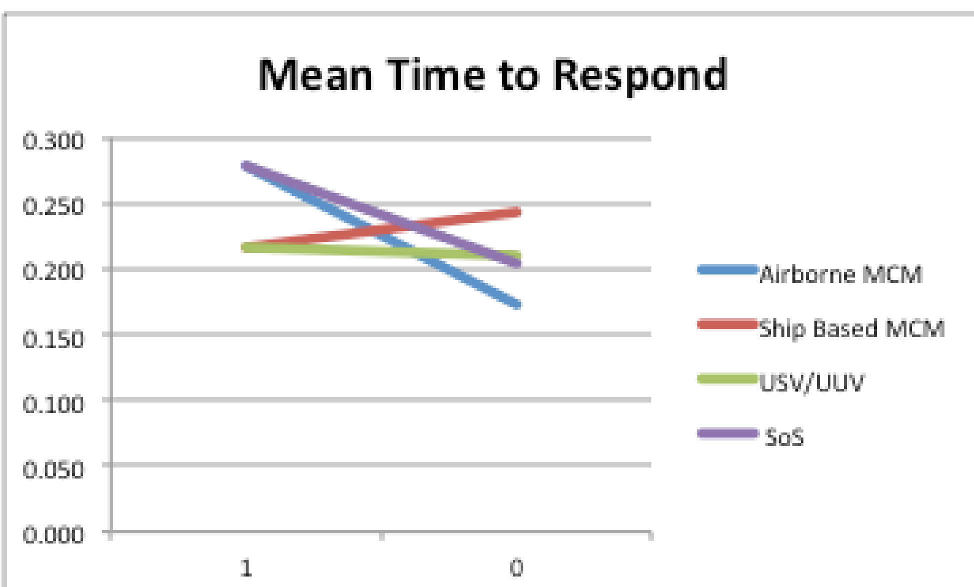


Figure 42. Mean Time to Respond

7. Magazine Supply

Figure 43 indicates that the preference of systems shifts from Ship Based MCM to a SoS approach at a weight of 0.277. Given the current weight of 0.025, this would constitute a 1012% increase in weight.

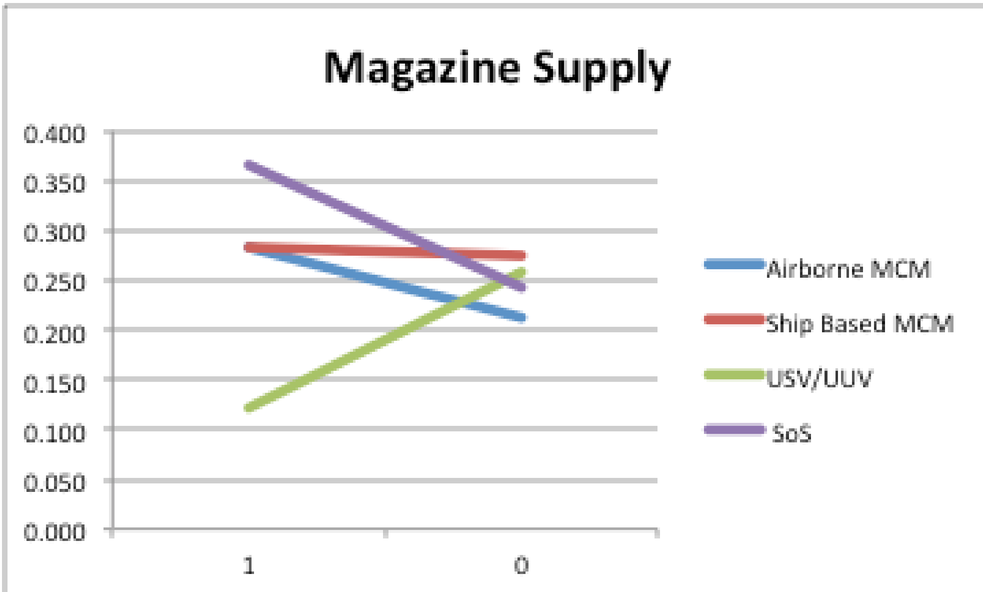


Figure 43. Magazine Supply

8. Rate of Fire

Figure 44 indicates that the preference of systems shifts from Ship Based MCM to an Airborne MCM approach at a weight of 0.425. Given the current weight of 0.040, this would constitute a 1302% increase in weight.

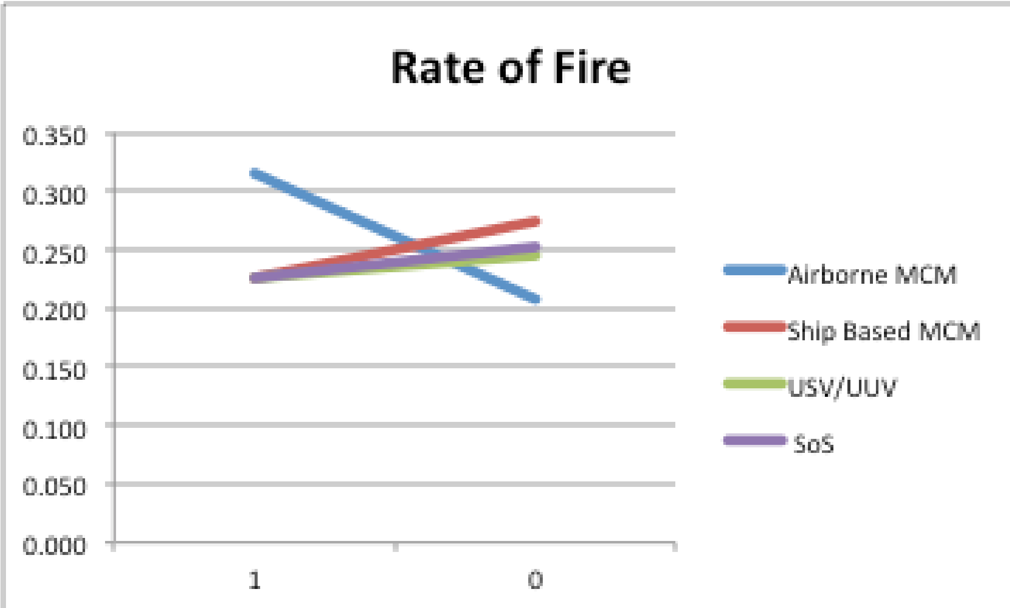


Figure 44. Rate of Fire

9. Engagement Range

Figure 45 indicates that the preferred alternative is insensitive to Engagement Range.

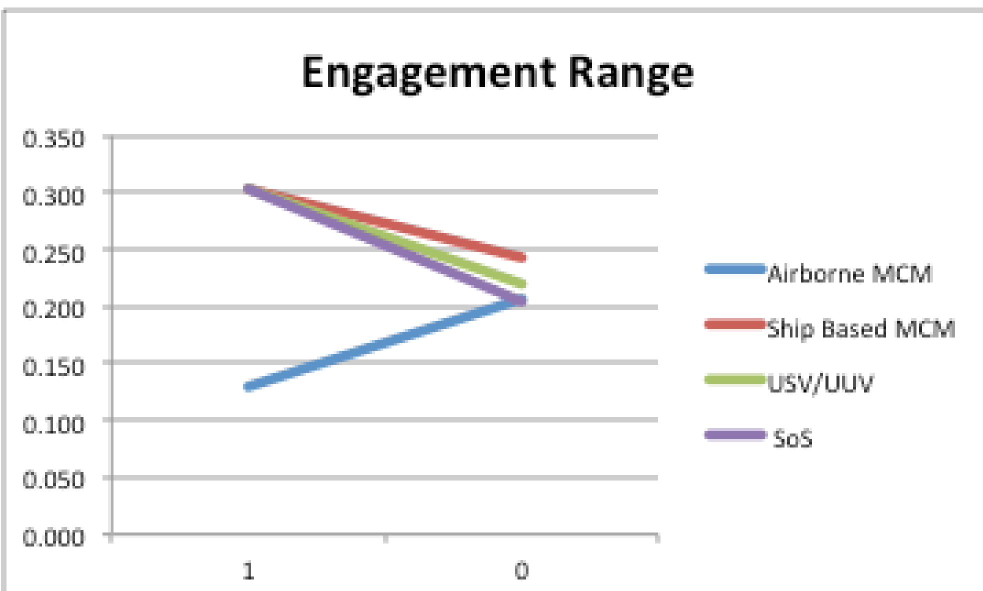


Figure 45. Engagement Range

10. Engagement Depth

Figure 46 indicates that the preference of systems shifts from Ship Based MCM to an Unmanned Surface Vehicle (USV/UUV) approach at a weight of 0.218. Given the current weight of 0.065, this would constitute a 237% increase in weight.

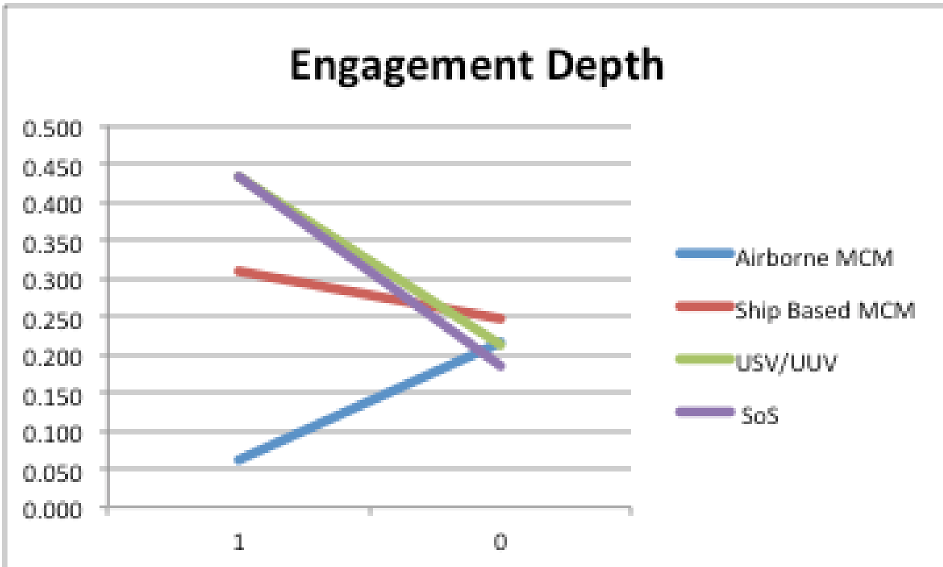


Figure 46. Engagement Depth

11. Cost Per Engagement

Figure 47 indicates that the preference of systems shifts from Ship Based MCM to a SoS approach at a weight of 0.113. Given the current weight of 0.100, this would constitute a 13% increase in weight. Therefore, the preferred alternative is highly sensitive to cost. Before opting for the Ship Based MCM approach, any decision-maker should invest in a complete Cost As Independent Variable (CAIV) analysis.

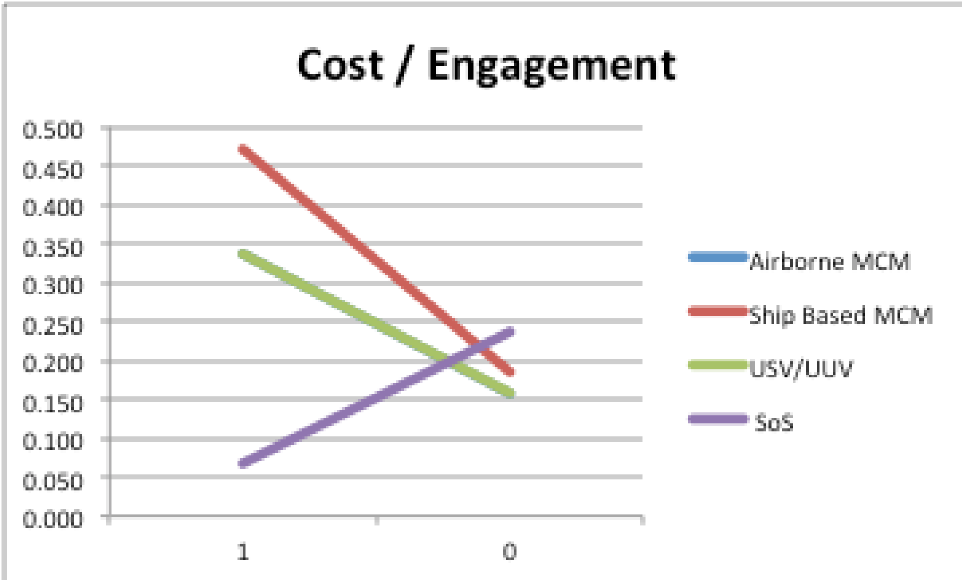


Figure 47. Cost vs. Engagement

12. Summary

With the exception of cost per engagement, the sensitivity analysis indicates that the preferred alternative does not shift from Ship Based MCM unless the stakeholder priorities are increased on the order of hundreds of percent as compared to the current values.

The cost per engagement sensitivity is a very important result as it shows that using the AHP process, where cost is an attribute of preference, cost remains a critical factor in selection. In a CAIV analysis, where the characterization of effectiveness would be divided by cost of the alternative, it is anticipated that cost would have a more profound impact on the preference selection. Therefore, the sensitivity analysis indicates that the Navy should consider both Ship-Based MCM and the System of Systems approaches that were described in this chapter in a Cost As Independent Variable (CAIV) analysis.

C. RISK AND COST CONSIDERATIONS

The International Council on Systems Engineering (INCOSE) defines programmatic risk as "A measure of the uncertainty of attaining a goal, objective, or requirement pertaining to technical performance, cost, and schedule."(INCOSE 2004)

Team Dahlgren assessed these primary components of program risk considering how they interact in Figure 48 and identified four specific areas of risk to the realization of an MCM point defense capability based on current technical, tactical, and political realities discovered during our open-source research.

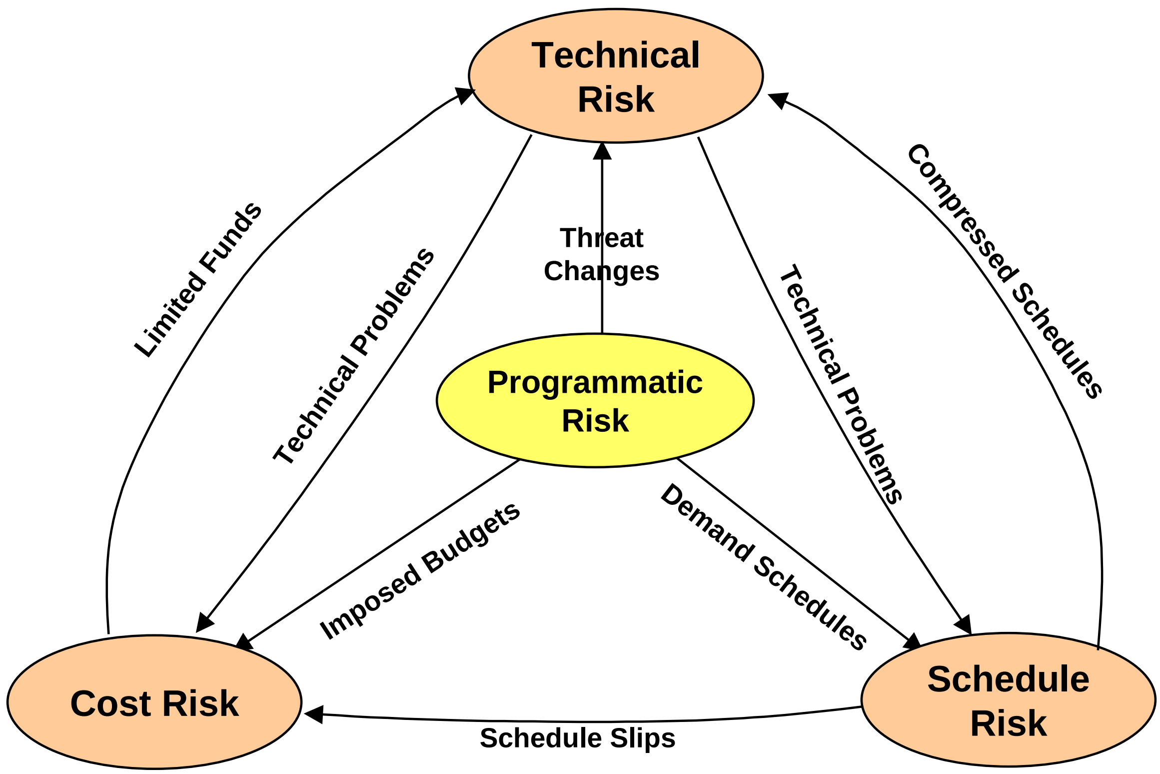


Figure 48. Typical Relationship among the Risk Categories (INCOSE 2004)

Threat Evolution: If mine technologies evolve such that smart, mobile mines become effective, then current MCM capabilities may be inadequate. While mine technology has remained simple in design and technique through much of the mine warfare age, the recent development and proliferation of MCM technologies in the last 20 years which enable mine detection, classification, and identification within the U.S. Navy have forced the evolution of naval mine triggering and concealment to a new realm of undeterred and undetected threats (James D. Bahr 2007). These so called “smart sea mines” are specifically designed to counter MCMs which detect classically deployed mines, “spoof” classically triggered mines (i.e. target differentiation to select specific fleet vessels) (Committee for Mine Warfare Assessment, Naval Studies Board, National Reseach Council 2001). In addition to the technical advancements of state actors in the

field of mine warfare, non-state actors have begun to present an asymmetric mine warfare threat. In terms of the Hague Convention (VIII) Provisions on mine warfare, asymmetric mining would consist of intentional intercepting of commercial shipping or the placement of uncontrolled or unmonitored automatic naval mines in any body of internationally accessible water(U.S. Joint Chiefs of Staff 2011). By employing these non-standard mine warfare tactics, small dissident groups would have the ability to greatly inhibit the power projection capabilities of the U.S. Navy and international commerce.

As asymmetrical employment of naval mine technologies and the use of smart mine technologies by state and non-state actors increases, the likelihood of non-MCM fleet vessels encountering an unmarked minefield or un-cleared mine will also increase. In order for an in-stride MCM point defense capability to be realized, mine detection, identification, and threat response (avoidance or neutralization) must be available on all naval and coast guard vessels rather than just dedicated MCM assets within the naval fleet.

Detection Challenge: If platforms are unable to detect the presence of a mine, then point-defense systems will be ineffective against the mine threat. While mine technology is constantly improving in terms of reduced sonar cross-sections and detection avoidance through mobility, the effectiveness of these signature reduction efforts remain dwarfed in comparison to environmental factors. In 2001, the Committee for Mine Warfare Assessment, Naval Studies Board, and National Research Council identified a few of these key environmental factors which have plagued MCM throughout the mine warfare age:

Bathymetry: The depth, slope, and roughness conditions of the mined waters affect the ability of Explosive Ordinance Disposal (EOD) personnel and mechanical sweep systems to counter deeply moored or surface laid mines.

Sound Propagation: Complex thermal distributions and sound velocity profiles and losses at the boundaries (bottom and sea surface) significantly affect acoustic propagation at the most likely mine locations.

Bottom Type and Composition: Bottom type (i.e. hard rock, firm sand, soft mud) largely determines the levels of bottom reverberation, clutter and roughs, and

bottom sediment type and thickness (along with bottom currents) establish the likelihood of mine burial and the ability to counter.

Non-mine Mine-like Bottom Object (NOMBO) Density: Debris and small bottom features influence the mine densities perceived by various active sonars. This parameter is sensitive to the characteristics of individual sonars including their spatial resolution and signal processing algorithms. High false alarm rates caused by high NOMBO densities will increase the risk of mine activation by reducing the ability to utilize more thorough mine hunting techniques due to transit time requirements and being forced to employ less thorough mine sweeping techniques.

Tides and Currents: Currents and tidal conditions can affect the performance of divers or remote vehicles, or even the ability of warships to execute controlled, slow-speed maneuvers to avoid detected objects that may be mines. Tidal currents and turbulence also cause natural fluctuations in pressure that can trigger pressure influence mines and promote mine burial, which will inhibit detection and identification.

Sea State: High sea state and wind conditions can increase ambient noise and surface reverberation and clutter; high sea states can also hamper sea keeping and MCM operations by limiting certain systems and techniques.

Water Clarity: Optical sensor performance (airborne or undersea) can vary appreciably depending on the optical clarity of the sea, which has a direct impact on laser and optical wavelength attenuation.

Current MCM methodology is heavily reliant on specifically localized environmental data, which is captured and evaluated just prior to employing MCM systems and techniques. In order to realize an in stride, MCM point defense capability for a non-MCM vessel, either the impact of these environmental factors must be greatly reduced through improvements in mine sensor technologies, techniques, and algorithms, or environmental characterization technologies, techniques, and algorithms.

Space-Capability Tradeoff: If mine point-defense capabilities require additional space onboard the protected platform, the platforms will have to sacrifice mission critical capabilities. In addition to the finite space constraints of equipping a naval warship, task

saturation during a multi-axis engagement must also be considered. Modern warships are designed and equipped to simultaneously combat a vast array of threats and complex engagement regions to include air, land, surface, and sub-surface. Despite these advancements in critical enabling technologies, the addition of an onboard MCM module and mission would inadvertently hinder a naval commander's ability to achieve sea control. A warship operating in a mined environment without the assistance of dedicated off-board MCM systems would have to significantly reduce its operational tempo and multi-tasking capabilities in order to safely prosecute mines. (Patrick A. Molenda 2005)

In order to realize an in-stride MCM point defense capability, the system must not inhibit the warship's primary warfighting requirements by either greatly reducing the size, weight, and power requirements of current systems or greatly increasing the MCM capability to a point that the current technology footprint is acceptable because the newly realized capability out weights the footprint burden. LCDR Molenda also suggests that risks to an on-board point defense MCM system could be greatly reduced if these systems were supported by an appropriately scaled, functional, and networked off-board MCM capability (organic MCM via system of systems), which would mean that the large portion of the mine threat had been cleared and the point-defense system was only charged with singular undetected mine defense.

MCM Infrastructure: If the U.S. Navy maintains or de-prioritizes MIW/MCM budget relative to the Naval table of allowances (TOA), then the threat to Navy platforms will grow as the cost of ships grows (or the capability of mines grow). Since the 1980's, the U.S. Navy has allotted about one to one and a half percent of the Navy TOA to MIW/MCM(Scott C. Truver 2012). While this small apportionment represents an obvious constraint on the pace at which MCM technology is developed, it more importantly reveals a larger issue of the lack of organizational prioritization, which will ultimately dominate the technology developmental curve. LTG Rhodes and RADM Holder dissected the reprioritization/mitigation areas of the Naval apportionment of resources to the MIW/MCM effort into the following categories in their future warfighting concept for MCM in littoral power projection (Rhodes and Holder 1998).

Leadership: The DoN will have to make a substantial investment in the research and procurement of the required MCM technologies, infrastructure, connectivity, threat and environmental knowledge with an increased consideration towards MCM operational tasking, proficiency, maintenance, and sustainment.

Education and Training: MCM education and training must evolve in two distinct and equal directions and in tempo with the deployment of innovative systems. First, MCM must be viewed as an equal partner among the traditional naval warfare areas and receive the necessary staffing and resources. Second, future MCM systems will employ state of the art technology, which will increase the necessary technical competency required to operate and maintain these systems.

Doctrine: Current MCM doctrine has remained largely unaltered since World War II, while all other naval warfare areas and elements have greatly increased in speed of maneuver and breadth of capabilities. In order to maintain pace with the future non-MCM naval capabilities, MCM technology will have to increase processing power by automating and streamlining the MCM kill chain. This introduction of technology and process will also require that the MCM lexicon be revised.

Material: Future MCM capabilities will require that the industrial and governmental technical/scientific communities be heavily engaged and resourced to develop effective, low cost, maintainable, modular, and flexible systems. Once material solutions or techniques or discovered to be effective, it is also incumbent upon the MCM community to protect and control the critical components and knowledge in order to limit the adversary's ability to counter the counter measure.

Organization: In order for fleet commanders to take advantage of organic MCM capabilities, the organization must be highly responsive, interoperable, and adaptive to changes in the operational situation and intent. In keeping pace with the non-MCM warfighting areas, effective C4I must allow MCM functions to be performed as a reach-back capability from various platforms in a highly dynamic and ever evolving operational environment.

Aside from the specific goal of achieving a capability to provide in-stride vessel protection through point-defense MCM, the need for U.S. forces to flatten the time vs. risk operational curve depicted in Figure 49 continues to drive the MIW/MCM community as it has been since the dawn of MIW.

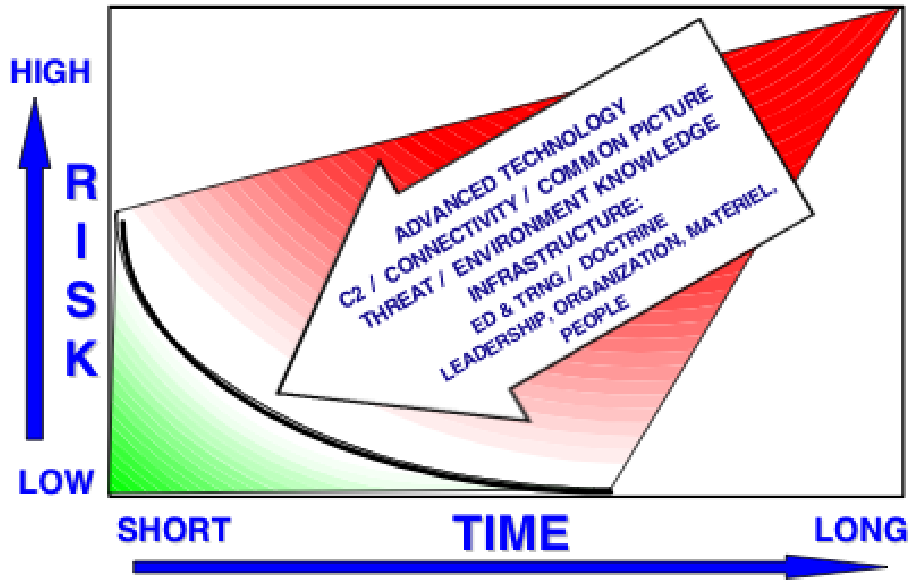


Figure 49. Future Operational Capabilities Goals - Time vs. Risk (Rhodes and Holder 1998)

To evaluate the contribution of mine point-defense to this risk vs. time trade-off. The team modeled the threshold and objective values varying the ship's approach speed. The results of this analysis are described in Table 21.

Table 21. Speed vs. Performance

	P(hit by mine)	
Speed	**Threshold**	**Objective**
3 kts	3.00%	0.00%
5 Kts	3.80%	0.00%
10 Kts	32.40%	0.00%
20 kts	N/A	0.00%
40 kts	N/A	0.20%
60 kts	N/A	2.40%
80 kts	N/A	3.00%

Table 21 shows that based on the approach speeds that are required for a specific set of missions—currently platforms traverse suspected minefields at roughly 5 knots (Fuller 2012)—a system that meets threshold values would be acceptable. However, as the protected platform increases its speed the risk increases by 1000% for a 50% reduction in time.

Operational risk and time to maneuver is mitigated through the optimal combination of technology and organization. Any developmental effort to advance MCM technologies will have to develop a robust integrated risk management plan, which leverages operational requirements, organizational resources, and technical capabilities to mitigate the inherent programmatic risks that, though well defined, continue to plague the MIW/MCM community.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This report documents research and analysis whose intent was to determine whether organic mine point-defense is a feasible solution to the mine threats. The analyses evaluated stakeholder preferences; modeled platform survivability under various performance characteristics; and compared technical parameters looking for interactions between parameters. The results of the analysis identified that system performance is constrained by accurate mine detection.

The Analytic Hierarchy Process analysis (IV.A) resulted in the recommendation that either a combination of shipboard, unmanned, and aerial systems connected in a System of Systems approach (as is the concept for LCS MCM MP) or a dedicated shipboard self-defense capability would be the optimum configuration for addressing organic mine point-defense. However, these configurations, using current technologies, would be constrained by fidelity of small-object detection underwater, and system cost.

B. RESEARCH QUESTIONS

1. How do Varying Navy Missions Impact Mine Point-Defense Strategy?

Four different projected operational scenarios were identified in this paper: Ship to Objective Maneuver; Transmitting Sea Lines of Communication; Joint Forcible Entry Operations; and Advance Clandestine Reconnaissance. The similarities in these missions are that the threatened platform must enter and traverse a mined area. The differences in the varying missions are number and size of protected platforms; and operational tempo.

The Advance Clandestine Reconnaissance mission may require defense of a single small, high-speed manned craft (such as an 8m RHIB); whereas the Transiting Sea Lines of Communications may require defense of multiple large destroyers, cruisers, carriers, etc. As a result, organic point defense needs to be a reliable, scalable, transportable capability with a short response time.

2. What is a Cost Effective Anti-Mine System?

The cost of mines can be expressed in two ways. First, the mines have a direct, monetary cost. When looking at the effectiveness of a mine as a mechanism for economic warfare, the analyst must compare the cost of the damaged platform (in the case of an incident) to the cost of the mine; or the analyst must compare the cost of the resources required to defeat the mine to the cost of the mine, itself.

This team's research was unable to obtain cost data for current mine countermeasure technologies; however, the PEO LCS MCM engineer with whom we consulted, indicated that no current MCM system competes with mines for cost effectiveness.

The second type of cost is a subjective valuation of 'access'. The value of access to certain strategic areas has the ability to offset the cost deficiency of mine operations (for example, prohibiting access to a major sea-base can have the effect of denying resupply to a combat force in a prolonged campaign); therefore, there are plausible scenarios where the value of the objective justifies the direct cost of the mine operations. This research was unable to provide an objective goal for the cost of mine defense systems, due to the limitations of current mine detection systems and the lack of availability of mine operation cost data. Nevertheless, mine defense opportunities must set cost efficiency as a top priority.

3. What are the Critical Attributes (and Critical Attribute Thresholds) for System Success?

The critical attributes that were identified throughout this project are listed in the table below. These attributes were used throughout the project in the QFD development as well as the modeling and simulation efforts. Given a platform speed of 5 knots and a mine blast radius of 60 m, the platform has a Probability of Survival of 96.2%

Table 22. Critical Attributes

Attribute	Threshold	Objective
Prob. Detection	0.4	0.6
Prob. Identification	0.6	0.8
Prob. Kill	0.6	0.75
Detection Range (m)	200	1000
Engagement Range (m)	100	500
Engagement Time (s)	2	0.5
False Alarm Rate	0.02	0.005
Sensor Cycle Time (s)	5	0.25

Along with the attribute identification, the SUTRS engineering team developed Threshold and Objective values for each. The Threshold and Objective values were derived from the M&S efforts once the main effects analysis was conducted. The goal of developing the Threshold and Objective values is to provide acceptable performance levels for each attribute as well as an ideal performance level. This provides a tradespace for the system developers and program office to work within. This tradespace is realized through the risk to the ship as well as the speed at which the ship can travel safely. This risk vs. time tradeoff is discussed in another research question.

4. How can "Layered" Mine Defense Improve Anti-Mine Operations' Risk vs. Time Tradeoff?

The concept of layered defense is not new, but analysis on how it impacts mine defense has not been fully explored. This question was addressed through the M&S efforts. Several ship speeds were input into the model along with the Threshold and Objective values for each attribute identified in research question III. Each combination of attributes and speeds was run through the model 500 times in order to have some statistical significance. The table below shows the results of this effort.

Table 23. Speed vs. Performance

	P(hit by mine)	
Speed	**Threshold**	**Objective**
3 kts	3.00%	0.00%
5 Kts	3.80%	0.00%
10 Kts	32.40%	0.00%
20 kts	N/A	0.00%
40 kts	N/A	0.20%
60 kts	N/A	2.40%
80 kts	N/A	3.00%

Note that speeds above 10 kts were not modeled with the Threshold values due to the high probability of being hit by a mine. This shows that based on the approach speeds that are required for a specific set of missions, a system that meets threshold values would be acceptable. However, if high rates of transit are required for a particular mission, then a point defense s system that meets objective values would reduce risk to the platform as a component of a layered defense model. Note that these values pertain to a situation where a mine is present and should not be considered an overall attrition rate. The risk of encountering a mine is mitigated in most situations by mine hunting and mine sweeping efforts that would occur before the SUTRS enabled ship enters the area. But currently, the application of mine point-defense does not improve upon the current technology's risk vs. time tradespace.

5. How will Future Mine Technologies Drive MCM Technology Development?

In many ways, this report is an answer to this question. Section I.D.3 discussed the current state of mine technologies and underwater threats based on bottom topography. In the current environment, bottom dwelling mines are the most difficult to properly prosecute (due to the inability to differentiate mines from bottom objects such as rocks) (Thompson and Bell 1997) as compared to mines suspended in the water column. Regardless, the current environment involves the platform approaching the mine. In the future, mines will approach the platform. For this type of environment, the currently employed mine countermeasure strategies (e.g., minesweeping) are inadequate. Instead,

the platform will require an ability to defeat the mine before it impacts the hull—point-defense—or the platform will require the ability to divert the attack to a non-threatening area—spoofing.

Therefore, given the results of the analyses described in this report, the development of future mine countermeasure systems would best benefit in sharing in the research into emerging underwater detection opportunities, such as the dolphin-esque capability to identify objects in the water through the use of pitch variations and non-linear math [need citation]. (Viegas 2012)

C. RECOMMENDATIONS

It is the recommendation of this report, given the cost of new system development and minimal impact to the risk vs. time tradeoff achieved through technologies modeled in this report, that the Navy continue to investigate the feasibility of new underwater technologies prior to substantially changing the Navy's development strategy for mine countermeasures. Additionally, given the criticality of the detection capability identified in the modeling and simulation efforts, it is recommended that the Navy specifically focus on improvements to small-object detection in the water column, because without improvements to the most critical aspect of mine point-defense, it is anticipated that the increase to platform survivability will not outweigh the sacrificed mission capabilities.

It should also be noted that the future of mine technologies would result in an environment where mines can approach the platform, instead of the current environment where the platform approaches the mine. This evolution could necessitate point-defense systems, as hunting and sweeping will not be sufficient for defending against a mobile mine threat. Therefore the future of mine countermeasures should include point-defense capabilities.

With this realization in mind, it is the recommendation of this report that the Navy should investigate the feasibility of improvements in the following three technological areas of opportunity:

1. High resolution 3-D sonars (or bathymetry sonars) capable of defining small objects at ranges greater than 100 meters.

High resolution 3-D sonars; often referred to as bathymetry sonars; capable of defining features of less than 2 inches are commercially available from a number of vendors but are very limited in terms of output power and range; typically tens of meters. For example one major vendor, BlueView Technologies™ Inc. produces and distributes a compact 3-D sonar; Model 2250-45; with resolution of less than 2 inches but which has a range of only 10 meters. (Blue View Technologies 2011)

The Office of Naval Research in June 2010 awarded a contract to BlueView Technologies™ Inc. to produce an enhanced version of this sonar model. (Blue View Technologies, Inc 2010) Performance metrics for this sonar were not available but the technology foundation is promising and investment in this capability should be continued.

2. Advanced digital signal processing algorithms that can provide detection and near optical resolution of fully-buried mine-like objects.

The Office of Naval Research provided a grant to Dr. David Pierson from North Carolina State University who demonstrated a unique approach to sonar imaging of buried objects in 2004. The novel approach used time domain signal reversal of a received target signal to “re-ping” a target and thereby provide a higher resolution sonar return. (Breakthrough Mine-Detection Turns Ocean Floor 'Transparent' 2004) No further information on the application of this technique was found but it does provide some insights into novel methods that in consideration of greater available processing power could, with focused investment, result in the acquisition of a key capability.

3. Low cost underwater kinetic systems that can engage submerged targets.

The RAMICS system identified earlier in the AoA is a kinetic mine engagement system deployed against surface or near-surface mines. The system uses a high velocity super-cavitating projectile that penetrates the mine casing to disable or destroy the mine. The system is deployed from a UH-60 helicopter, and because of the danger from the potential explosion, has not been widely utilized.

Despite the RAMICS system shortcomings, the concept of a super-cavitating ballistic has potential for further development as a fully underwater kinetic engagement capability.

Conversations with NUWC research scientists indicate that a number of promising kinetic kill system technology concepts for use against underwater munitions, while not currently available, are being researched. (Lead, NUWC Newport Innovative Technologies 2012) Among these technology concepts are super-cavitating hydro-ballistics; projectiles that would utilize an underwater gun system; and super-cavitating pulsed water-jet systems that could be employed on small UUVs.

Super-cavitating hydro-ballistics could support a fast response kill system that is effective at ranges over 100 meters. The super-cavitating pulsed water-jet systems have slower response times and require the UUV to operate at close ranges; less than one meter. (NUWCDIVNPT Technology Proposal 2012) However, with the exception of onboard power, these jet systems would have a virtually unlimited magazine. Funding would have to be obtained in order to further progress in these areas.

4. Advanced non-linear echolocation techniques capable of detecting small objects in turbulence.

Due to the cost realities of mine warfare, it is the recommendation of this report that the Navy should seek commercial applications of these capabilities in the interest of sharing costs with corporate partners.

As we project into the future of mine warfare capabilities, current MCM practices and capabilities will not keep pace with the operational capability of naval mine technologies and the need for a platform based mine point-defense system will grow.

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APPENDIX A

A. ENVIRONMENTAL CHARACTERISTICS

The SUTRS system will be required to operate in various oceanic environments. Definitions of these oceanographic characteristics are adapted from (OPNAVINST 3500.38B/MCO 3500.26A/USCG COMDTINST M3500.1B 2007) and are provided in Table 25.

Table 25. Environmental Characteristics

Environmental Element	Element Definition	Element
Sea	Those factors associated with the continuous salt water ocean system to include oceans, seas, gulfs, inlets, bays, sounds, straits, channels, and rivers.	Open (open ocean, blue water beyond 5 NM of land) Littoral (Coastal, (within 5 NM of land areas) Riverine (inland from the littoral terrain to include rivers, canals, and delta areas connected to landlocked waters)
Ocean Waters	Primary bodies of salt water that are not landlocked.	Atlantic (North and South) Pacific (North and South) Indian Arctic
Ocean Depth	The depth of ocean water at a point or for an area.	Very shallow (<50 fathoms) Shallow (50 to 100 fathoms) Limited (100 to 500 fathoms) Deep (500 to 2500 fathoms) Very deep (> 2500 fathoms)
Ocean Currents	A steady, generally predictable flow, present either in open ocean waters or in littoral coastal ocean waters.	Strong (> 3 knots) Moderate (1 to 3 knots) Little or no (< 1 knot)
Sea State	Roughness of seas caused by wind or disturbances.	Calm to slight (Beaufort Force < 5, Sea State 3 or less, seas 4 ft or less) Moderate (Beaufort Force 5, Sea State 4, seas 4-8 ft) Rough (Beaufort Force 6-7, Sea State 5-6, seas 8-16 ft) Very Rough (Beaufort Force 8-9, Sea State 6, seas 17-20) High (Beaufort Force 10, Sea State 7, seas 20-

Environmental Element	Element Definition	Element
		30 ft) Extremely rough (Beaufort Force above 10, Sea State above 7, seas above 30 ft)
Ocean Temperature	Water surface temperature (degrees Fahrenheit).	Extremely cold (< 35 F) Cold (35 to 55 F) Moderate (56 to 75 F) Warm (> 75 F)
Saline Content	Level of salt content in water (parts per thousand).	Low (< 25 0/00) Average (25 to 35 0/00) High (> 35 0/00)
Ocean Features	Features just above, just below, or within 10 fathoms of the ocean surface to include islands, atolls, reefs, shoals, rocks, or icebergs.	Large raised (islands) Small raised (atolls, reefs) Small submerged (rocks, icebergs) Large submerged (shoals, subsurface reefs)
Sea Room	Availability of space for maritime maneuver. Includes dynamic factors such as confining ice, submerged wrecks, or potentially damaging floating objects such as logs. Applies especially to coastal polar, littoral, or riverine environments.	Unrestricted (open ocean) Moderate (some confining factors) Confined (coastal and riverine waters)
Ocean Acoustics	Assessed qualities of the tactical subsurface environment, including factors such as sound propagation path, layer depth, and propagation loss (but excluding sea state, ambient noise and other factors covered separately in this section) that affect the ability to detect objects.	Good (subsurface detection systems operate effectively in the acoustic environment) Fair (systems moderately degraded by acoustic conditions) Poor (systems severely degraded by acoustic conditions)
Ocean Bioluminescence	Emission of visible light by living marine organisms.	Bright (significantly enhances visibility near water surface) Noticeable (provides some additional light near water surface) No
Ocean Fronts	Fronts are tactically	Significant (fronts and eddies will have a

Environmental Element	Element Definition	Element
and Eddies	significant discontinuities in the water mass, such as horizontal temperature gradient, which significantly alter the pattern of ocean acoustics. Eddies are circular fronts that have broken off from a strong front such as the Gulf Stream.	major impact on the ability to detect subsurface objects) Moderate (not the central factor in acoustic conditions) Negligible
Divers/Swimmers Underwater Visibility	The maximum distance objects can be seen at the depth which underwater operations are being conducted.	Zero (<1 foot) Poor (1-5 feet) Fair (6-10 feet) Good (11-50 feet) Excellent (51-200 feet) Unlimited (>200 feet)
Ocean Bottom	The characteristics of the sea bottom.	Regular (no significant features) Irregular (sea bottom irregularities)
Sea Bottom Contours	Gradient of the seabed.	Flat (floors of ocean basins, plains) Gentle (continental shelf) Moderate (ridges, fracture zones) Steep (trenches, sea mounts)
Sea Bottom Composition	Seabed material from the ocean bottom to the shore.	Sandy Silty Rocky
Harbor Depth	Water level at low tide.	Deep (> 60 ft) Moderate (30 to 60 ft) Shallow (< 30 ft-May not be able to handle fully-loaded ships)
Harbor Currents	Moving water caused by tidal change and river runoff.	Fast (> 3 knots) Moderate (1 to 3 knots) Negligible (< 1 knot)
Coastal Characteristics	Characteristics of the shore area, including contiguous waters and land areas.	Harsh (difficult grades, surfaces, inshore currents extensive obstacles) Moderate (moderate grades, currents some obstacles) Mild (gentle natural factors} No obstacles
Coastal Gradient	Slope of the beach, from low tide up to the extreme high tide mark.	Gentle (< 2%) Moderate (2 to 5%) Steep (> 5%)

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APPENDIX B

Purpose:

The Mine Countermeasures (MCM) Stakeholder Survey is intended for military and/or civilian MCM professionals. The survey will be used to assess and categorize system performance attributes that a conceptual MCM system would need to exhibit. The survey will begin by requesting professional demographic information in order to attribute individual perceptions to stakeholder areas of interest. The primary questionnaire section will present a number of statements of comparison between two MCM system attributes, which will require a selected level of comparative criticality. This survey does not collect or use personally identifiable information and is not retrieved by personal identifier. Therefore, the information collected is not subject to the Privacy Act of 1974.

All survey questions are answerable by selecting the most appropriate statement of agreement with the posed query.

Professional Demographic:

The information provided below WILL NOT be used to identify you. It is used by the MCM development team to associate individual responses with identified stakeholder groups.

1. My age is

   1 = 18 – 21
   2 = 22 – 30
   3 = 31 – 40
   4 = 41 – 50
   5 = 51 or over

Comment:

____

2. I was or currently am in the following position(s) [please select all that apply to you]:

   1 = Military Officer
   2 = Warrant Officer
   3 = Enlisted Member
   4 = Federal Civilian Employee

5 = Federal Civilian Contractor

Comment:

---

3. What is the best description of your MCM professional experience? (select all that apply to you)

   1 = Military User
   2 = Program Manager
   3 = System Developer
   4 = Intelligence Analyst
   5 = None

Comment:

For questions 4 through 12, refer to a theoretical system that will be used to protect Navy platforms from mine threats. The theoretical system has the following ten critical system attributes:

MC.1 Mission Planning: the ability to develop, maintain, execute, and coordinate anti-mine operation mission plans.

MC.2 Environmental Characterization: the ability to identify mission critical environmental characteristics in support of anti-mine operations.

MC.3 Underwater Object Detection: the ability to detect underwater objects within a specific minimum range required to conduct anti-mine operations.

MC.4 Underwater Object Identification: the ability to characterize detected underwater objects within a specific minimum range required to conduct anti-mine operations.

MC.5 Command and Control: the ability to provide or leverage comprehensive capabilities necessary for command, control, communications, computers & information networking among MCM assets.

MC.6 Underwater Threat Response: the ability to eliminate (or otherwise render safe) underwater objects determined to be a critical threat to the surface unit.

MC.7 Survivability: the ability to operate in an operationally contested environment to include natural and man-made environmental conditions.

MC.8 Availability: the probability that a system, when used under stated operational/support conditions, will operate satisfactorily when called upon.

MC.9 Interoperability: the ability to integrate current and future sensor systems through a common physical and data interfaces based on open system architectures.

MC.10 Environmental Compatibility: the ability to operate in the maritime environment under varying conditions of temperature, pressure (depth from surface), salinity, sedimentation, and chemically degraded environments.

In questions 4 through 12, you will be asked to compare nine of the above attributes to one common reference (i.e., Underwater Threat Response). In each question, you will be asked to rate the impact of the reference relative to another attribute (e.g., Command and Control, Availability) using the scale below:

Much More Critical
More Critical
Equally Critical
Less Critical
Much Less Critical

Please <u>PLACE AN "X"</u> in the selected comparative level of criticality.

(Note: The above options are arranged spatially on the following page such that placing an "X" closer to the more critical object will reflect the appropriate level of criticality.)

	Much More Critical		More Critical		Equally Critical		Less Critical		Much Less Critical	
. Underwater Threat Response is…										…than Mission Planning.
. Underwater Threat Response is…										…than Environmental Characterization.
. Underwater Threat Response is…										…than Underwater Object Detection.
. Underwater Threat Response is…										…than Underwater Object Identification.

	Much More Critical		More Critical		Equally Critical		Less Critical		Much Less Critical	
. Underwater Threat Response is…										…than Command and Control.
. Underwater Threat Response is…										…than Survivability.
Underwater Threat Response is…										…than Availability.
Underwater Threat Response is…										…than Interoperability.
Underwater Threat Response is…										…than Environmental Compatibility.

Table 24. Pair-wise Comparison for Stakeholder Survey

Criteria	Criteria	Underwater Threat Response 1	Mission Plannning 2	Environmental Characterization 3	Underwater Object Detection 4	Underwater Object Identification 5	Command and Control 6	Survivability 7	Availability 8	Interoperability 9	Environmental Compatibility 10	Weights
Underwater Threat Response	1	1	4.6	6.2	1.5	1.5	2.2	1.8	4.2	4.6	6.2	0.2288
Mission Plannning	2	0.2	1	1.3	0.3	0.3	0.5	0.4	0.9	1	1.3	0.0497
Environmental Characterization	3	0.2	0.7	1	0.2	0.2	0.4	0.3	0.7	0.7	1	0.0369
Underwater Object Detection	4	0.7	3.1	4.2	1	1	1.5	1.2	2.9	3.1	4.2	0.1558
Underwater Object Identification	5	0.7	3.1	4.2	1	1	1.5	1.2	2.9	3.1	4.2	0.1565
Command and Control	6	0.5	2.1	2.8	0.7	0.7	1	0.8	1.9	2.1	2.8	0.1040
Survivability	7	0.6	2.6	3.4	0.8	0.8	1.2	1	2.3	2.6	3.4	0.1271
Availability	8	0.2	1.1	1.5	0.3	0.3	0.5	0.4	1	1.1	1.5	0.0545
Interoperability	9	0.2	1	1.3	0.3	0.3	0.5	0.4	0.9	1	1.3	0.0497
Environmental Compatibility	10	0.2	0.7	1	0.2	0.2	0.4	0.3	0.7	0.7	1	0.0369
		0.2	0.0	0.0	0.2	0.2	0.1	0.1	0.1	0.0	0.0	1.0000

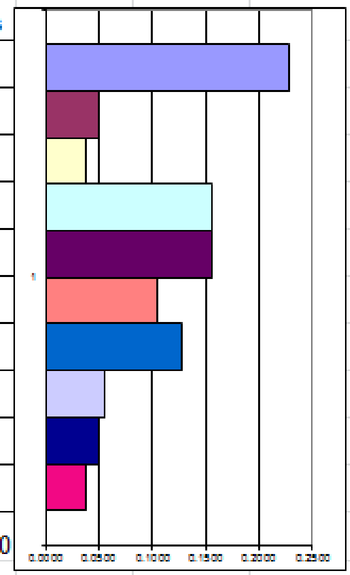


Table 25. QFD 1

Design Characteristic (Hows)

Customer Requirement (Whats)	Weights		Time to Plan	Time to Characterize Environment	Probability of Detection	Detection Cycle Rate	Detection Range	Probability of Identification	False Alarm Rate	Mean Time to Identify	Mean Time to Respond	Probability of Success	Magazine Supply	Rate of Fire	Engagement Range	Engagement Depth	Operational Availability	Mean Time Between Failure	Mean Time to Repair	Mean Logistic Delay Time	
Threshold			120	240	0.4	0.2	200	0.6	0.02	4	2	0.6	10	0.2	100	40	0.8	600	24	96	
Objective			30	20	0.6	4	1000	0.8	0.005	1	0.5	0.75	30	1	500	300	0.95	1000	4	48	
			min	min	unitless (per scan)	Scan / second	m	unitless (per mine)	%	sec	sec	unitless (per mine)	engagements	engagements / sec	m	ft	%	hrs	hrs	hrs	
Underwater Threat Response	0.2288	0.229	1	1	3	3	3	3	3	3	9	9	3	3	9	9	1	1			
Mission Plannning	0.0497	0.050	9	3																	
Environmental Characterization	0.0369	0.037		9												1					
Underwater Object Detection	0.1558	0.156	1		9	9	9										1	1			
Underwater Object Identification	0.1565	0.156	1		3		3	9	9	9							1	1			
Command and Control	0.104	0.104			1		1	1	1	1	9	3		3	3		1	1			
Survivability	0.1271	0.127															3	9	3		
Availability	0.0545	0.054			3	3		3				3	3				9	3	9	9	
Interoperability	0.0497	0.050									3				1		1	1	3	1	
Environmental Compatibility	0.0369	0.037		1	1		1	1	1	1	1	1		1	1	3	3	3	1	1	
Check Sum		1.00																			
Weighted Performance			1.0	0.7	2.9	2.3	2.7	2.4	2.2	2.2	3.2	2.6	0.8	1.0	2.5	2.2	1.7	2.1	1.1	0.6	34.1
Percent Performance			0.029	0.022	0.084	0.066	0.079	0.070	0.065	0.065	0.093	0.075	0.025	0.030	0.072	0.065	0.049	0.062	0.031	0.017	

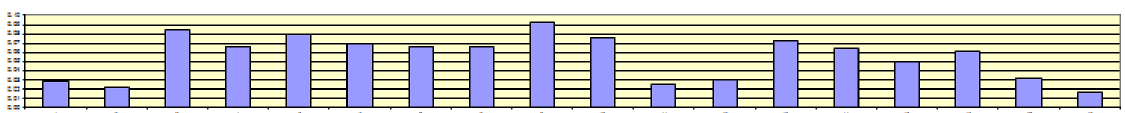
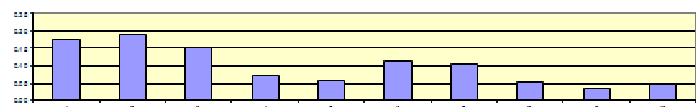


Table 26. QFD 2

Design Characteristics (Whats)	Weights		Detect Underwater Objects	Identify Underwater Objects	Neutralize Underwater Objects	Avoid Underwater Objects	Defend (Passive) Against Underwater Objects	Command and Control Underwater Engagement	Travel to Mine	Navigate	Characterize Environment	Plan Mission	
			Units	Units	Units	Units	Units	Units	Units	Units	Units	Units	
Time to Plan	0.029	0.029						1			3	9	
Time to Characterize Environment	0.022	0.022						1			9	1	
Probability of Detection	0.084	0.084	9	3					3	1	1	1	
Detection Cycle Rate	0.066	0.066	3										
Detection Range	0.079	0.079	9	3						1			
Probability of Identification	0.070	0.070	3	9				1	3	1	1	1	
False Alarm Rate	0.065	0.065	3	9				1	1			1	
Mean Time to Identify	0.065	0.065		9				3	3			1	
Mean Time to Respond	0.093	0.093			3	3		9	3			1	
Probability of Success	0.075	0.075			9	9	9	3	3	1	1	1	
Magazine Supply	0.025	0.025			1								
Rate of Fire	0.030	0.030			3			1					
Engagement Range	0.072	0.072	3	3	9					1			
Engagement Depth	0.065	0.065			3								
Operational Availability	0.049	0.049	3	3	3	1	1	3	3	3			
Mean Time Between Failure	0.062	0.062	3	3	3	1	1	1	3	3			
Mean Time to Repair	0.031	0.031	1	1	1	1	1	1	1	1			
Mean Logisitic Delay Time	0.017	0.017	1	1	1	1	1	1	1	1			
Check Sum	1.000	1.00											
Weighted Performance			2.7	2.9	2.3	1.1	0.8	1.7	1.6	0.8	0.5	0.7	15.2
Percent Performance			0.176	0.191	0.151	0.074	0.055	0.114	0.106	0.050	0.034	0.049	

Functions (Hows)



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